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

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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 LaBr₃(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 will be 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 involved. A key tool used in the understanding of the inner workings of nuclei is through the study of nuclear structure. One major application of this information is in the indirect determination of 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 calculations of the reaction rates from that information. In addition, the nuclear structure information may 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 (G.R. Satchler 1983). In addition to permitting measurement of excitation energy, transfer reactions will selectively populate certain states depending on the chosen reactants that enable spin-parity assignments of those levels. β -decay measurements, including β -delayed neutron emission studies, allow for measurement 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 poor reconstruction of excitation energy. By measuring the coincident γ -ray, 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. 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 separating the particle associated with a 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 provide 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 a γ -ray detector 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) seeks to provide a flexible configuration of γ -ray detectors. Some previous detector systems designed for measuring particle- γ coincidence, such as TREX + Miniball (V. Bildstein *et al.* 2012), 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 $2 - 6^\circ$, 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) (A. Ratkiewicz *et al.* 2013), which improves the angular resolution, roughly 1° , but comes at the cost of requiring significantly more high-purity germanium (HPGe) detectors and associated infrastructure to maintain 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.

To address this balance between γ -ray efficiency and particle angular resolution, HAGRiD is 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 provide 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 we have selected to use BrillanCe 380 LaBr₃(5% Ce) scintillators manufactured by Saint-Gobain Crystals (A. Iltis *et al.* 2006) for HAGRiD. The array is currently composed of twenty-seven 2"×2" cylindrical crystals with the addition of ten 3"×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 between 2"×2" scintillators is on the order of a few hundred picoseconds for a ⁶⁰Co source.

We have selected Hamamatsu R6231-100 two inch photomultiplier tubes (PMTs) to be used in conjunction 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 (K. Nakamura *et al.* 2010) 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 LaBr₃(Ce) scintillators currently coupled with HELIOS (A. Arcones *et al.* 2016). As HAGRiD crystals are of similar dimension to Apollo units, the two detectors from these two arrays can easily be coupled together

3. First Experiments

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.

3.1. β -delayed Neutron Emission Studies at Hollifield 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) (W.A. Peters *et al.* 2016). The first of these measurements was performed at the Hollifield Radioactive Ion Beam Facility (HRIBF) (D.W. Stracener 2003) 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 (J.A. Winger *et al.* 2009). In addition, the reactor anti-neutrino anomaly may be, in part, due to an underestimation of the beta-delayed neutron emission branching (A.A. Sonzogni *et al.* 2015).



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.

A beam of isotopes of interest was produced by the On-Line Test Facility (OLTF) (H.K. Carter and D.W. Stracener 2008). 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 (R.C. Haight *et al.* 2012 and H.Y. Lee *et al.* 2013). 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 a portion of a collection of γ -ray detectors, shown in Fig. 1 which included sixteen 2"×2" HAGrID detectors (assembled with R7724 SEL PMTs), 10 NaI(Tl) scintillators, and a single HPGe clover detector from the Clover Array for Radioactive ION beam (CLARION) (C.J. Gross *et al.* 2000). 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 – 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% (Mazzocchi *et al.* 2005). Recent studies in this region (M. Madurga *et al.* 2016 and A. Spyrou *et al.* 2016) have indicated that the β -decay strength is enhanced compared to current theoretical models (P. Möller. 2012).

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.

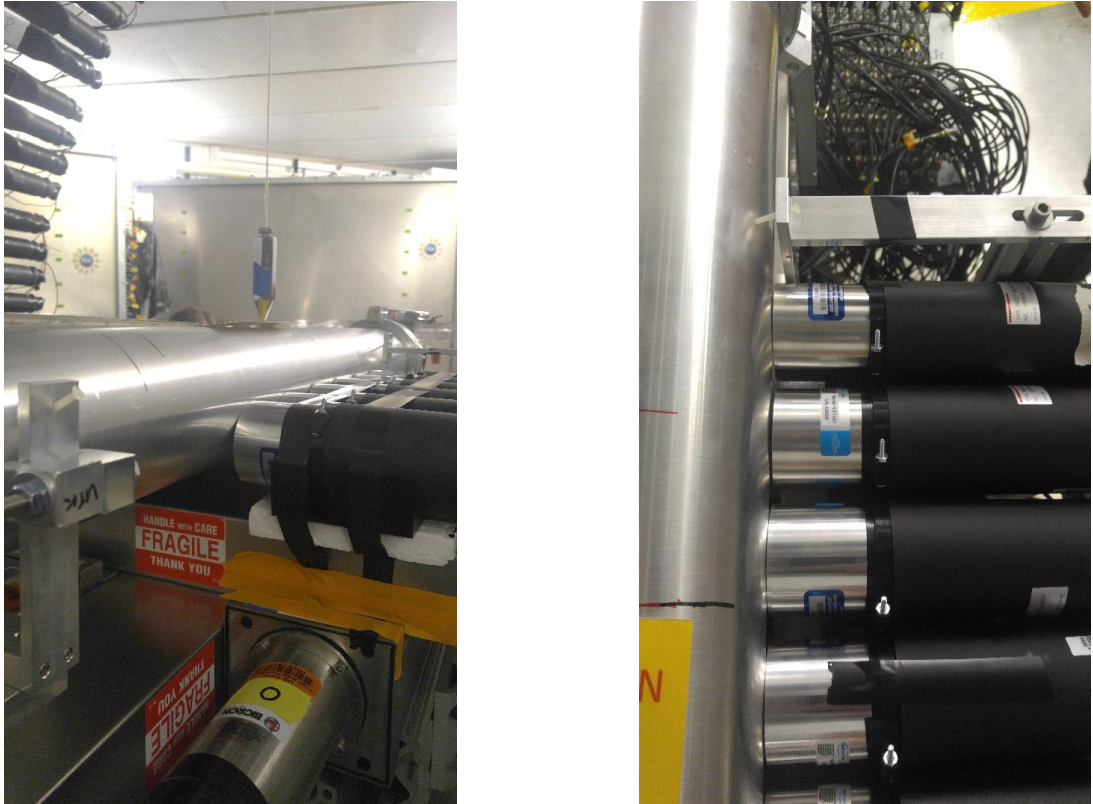


Fig. 2. Setup of β -delayed neutron emission of neutron-rich cobalt isotopes study at the NSCL. (a) Beam line (beam entering from left to right) surrounded with VANDLE (top left), NaI(Tl) detectors (below) and HAGrID (right). The implantation detector is not visible within the beam line. (b) A close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

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) (S.D. Pain *et al.* 2007) of silicon charged particle detectors, specifically super ORRUBA detectors, were placed around the Jet Experiments in Nuclear Structure and Astrophysics (JENSA) (K.A. Chipps *et al.* 2014) at the ReA3 facility (O. Kester *et al.* 2009) of the NSCL in February and May of 2016. The measurement was designed to improve understanding of the astrophysical reaction $^{34}\text{Ar}(\alpha, p)^{37}\text{K}$ which plays a role in the αp -process expected to occur during an X-ray burst on the surface of an accreting neutron star (R.H. Cyburt *et al.* 2016).

These studies included a commissioning run of JENSA in addition to the first direct measurement of the $^{34}\text{Ar}(\alpha, p)^{37}\text{K}$ 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 a density of about 10^{19} atoms/cm². Reaction protons, as well as scattered α particles, were detected in the ORRUBA 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), 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% at 1332 keV. A preliminary online γ -ray spectrum in coincidence with protons from the $^{14}\text{N}(\alpha, p)^{17}\text{O}$ 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 S. Konrad *et al.* 2016 and K.A. Chipps *et al.* 2017.

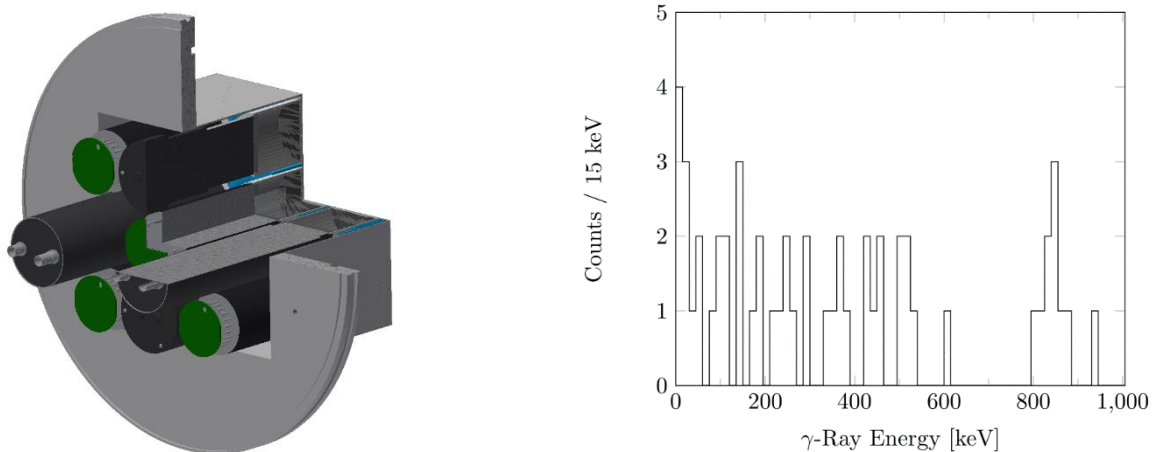


Fig. 3. (a) Three-quarter section drawing of the HAGRiD arrangement within the recessed flange. The central detector is placed facing the reaction region at 90° from the beam axis. (b) Preliminary online γ -ray spectrum gated on coincident protons from $^{14}\text{N}(\alpha, p_1)$, the 871 keV line from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

3.4. Measurement of the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ Reaction Cross-Section

HAGRiD was used at the Nuclear Structure Laboratory at the University of Notre Dame in May of 2016 in a measurement seeking to better understand the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction. This reaction is often a source of background in many other measurements (G. A. Jones and D. H. Wilkinson 1953, S. Abe *et al.* 2008, and F.P. An *et al.* 2012). A beam of α particles was produced by the Stable ion Accelerator for Nuclear Astrophysics (Santa ANA), a National Electrostatics Corporation 5U Van de Graaff accelerator capable of producing 5 MV potential and delivering beams exceeding $100 \mu\text{A}$ (Z. Mesiel *et al.* 2017). The beam was transported to the stopped-beam beamline and then impinged on a target of ^{13}C . Emitted neutrons were measured with a deuterated liquid scintillator from the University of Michigan Deuterated Scintillator Array (UM-DSA) (M. Febraro *et al.* 2015). γ -rays emitted from the de-excitation of ^{16}O were measured by $2'' \times 2''$ HAGRiD (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. Figure 4 shows a picture of the setup.

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 $2'' \times 2''$ detectors is ongoing. The $3'' \times 3''$ 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.

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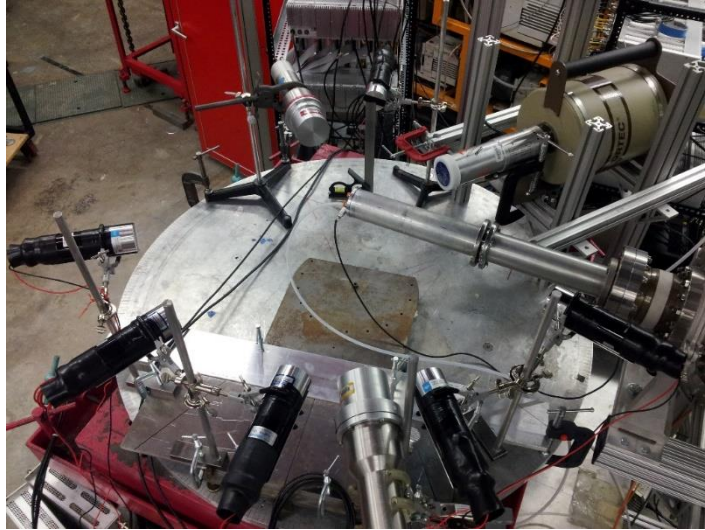


Fig. 4. Picture of setup used for measurement of $^{13}\text{C}(\alpha, n)^{16}\text{O}$. Visible is the implantation target (long cylinder coming from right side of the page) surrounded by one HPGe, two deuterated liquid scintillators from UM-DSA, and six $\text{LaBr}_3(\text{Ce})$ from HAGRID.

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