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Direct reaction measurements using GODDESS

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Abstract

GODDESS is a coupling of the charged-particle detection system ORRUBA to the gamma-ray detector array Gammasphere. This coupling has been developed in order to facilitate the high-resolution measurement of direct reactions in normal and inverse kinematics with stable and radioactive beams. GODDESS has been commissioned using a beam of ^{134}Xe at 10 MeV/A, in a campaign of stable beam measurements. The measurement demonstrates the capabilities of GODDESS under radioactive beam conditions, and provides the first data on the single-neutron states in ^{135}Xe, including previously unobserved states based on the orbitals above the N=82 shell closure.

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1. Introduction

Direct reactions are a cornerstone of our understanding of nuclear structure, providing experimental constraint on the single-particle and collective properties of nuclear states. Though studied for decades using beams of light ions incident on heavier target nuclei of interest (*normal kinematics*), in general such reactions must be employed using a beam of the heavy nuclei of interest, and a light-ion target (*inverse kinematics*), in order to be practically applicable to all isotopes, stable and radioactive. Though the inverse-kinematics technique can be exploited for the study of more nuclides (in principle, any which can be made into a beam) it carries a number of well-documented experimental challenges, including kinematic compression, increased target-induced kinematic broadening, and backgrounds from fusion-evaporation reactions of the beam on the carbon component of the deuterated plastic targets usually employed.

For many direct reaction measurements, the detection of gamma rays in coincidence with charged particles is either necessary (Coulomb-excitation measurements, for instance) or highly advantageous. For measurements such as particle transfer reactions, gamma rays aid significantly in separating closely-spaced states populated in the reaction. In addition to the improved energy resolution of gamma-ray detection compared to particle-derived measurements, in many cases neighboring levels proceed via decay to different states, leading to better separation in gamma-ray energy than simply the difference in excitation energy. Furthermore, gamma rays carry additional information on the states populated and their decay modes, and can provide information on states not populated directly in the transfer reaction. In the surrogate technique for constraining statistical neutron capture through a compound nucleus (J. Escher *et al*. 2012), for example, low-lying collecting transitions are used to determine the gamma branches of collections of nuclear states in the continuum, populated just above the neutron separation energy (as determined by detection of the ejectile).

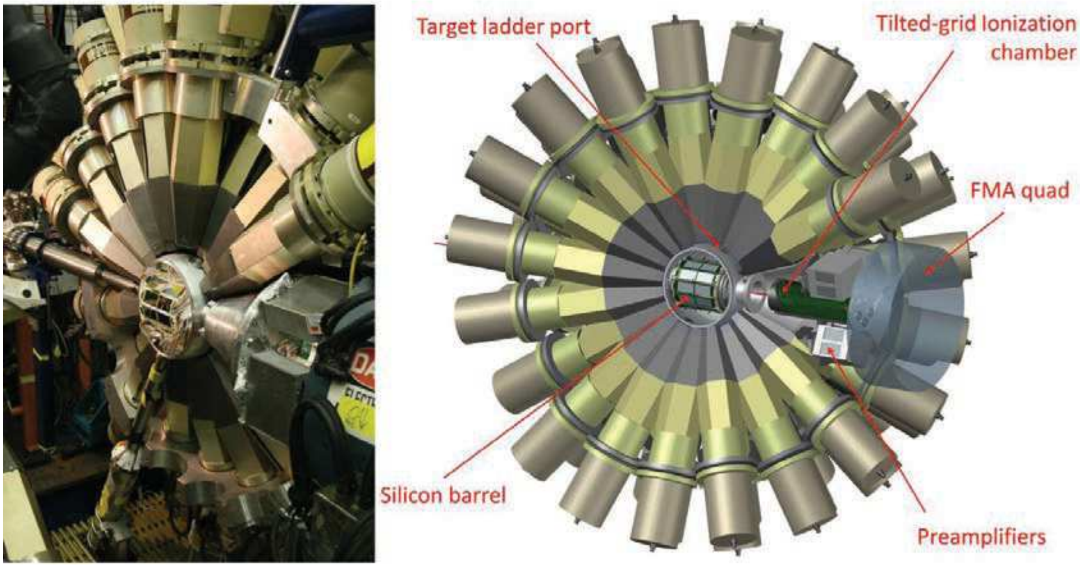
The locations and properties of low-spin states with single-particle character often dictate thermonuclear reaction rates in astrophysical environments, impacting elemental and isotopic abundances from, and the energetics of, astrophysical phenomena (stars, novae, x-ray bursts, etc). Single-nucleon transfer reactions involving hydrogen isotopes are well-characterized probes of single-particle states and their mixing, yielding excitation energies, spin-parity assignments, and spectroscopic information on the levels populated. Such information can be used to constrain the properties of the astrophysically-important states so that astrophysical reaction rates, many of which cannot be constrained by direct measurement, can be calculated.

2. Design of GODDESS

2.1. Overview of GODDESS

In order to facilitate direct-reaction measurements in inverse kinematics, a coupling of the charged particle detector ORRUBA (S. D. Pain *et al.* 2007) (Oak Ridge Rutgers University Barrel Array) and the Gammasphere (I.-Y. Lee 1990) array of HPGe detectors has been undertaken. This coupled system, named GODDESS (Gammasphere ORRUBA: Dual Detectors for Experimental Structure Studies) (A. Ratkiewicz et al., 2013, S. D. Pain 2014, S. D. Pain *et al.*, 2017), is designed for high-resolution particle-gamma measurement of reactions with stable and radioactive beams, including beams of fission fragments from CARIBU (G. Savard *et al.*, 2015), and lighter ($A < \sim 30$) beams produced in-flight at the ATLAS facility at Argonne National Laboratory (from the present in-flight facility, and the AIRIS upgrade currently under development (AIRIS 2017)). A photo of GODDESS, along with an annotated CAD drawing, is shown in Figure 1.

Fig. 1. Photo (left panel) and CAD representation (right panel) of GODDESS.



2.2. GODDESS silicon array

Inside Gammasphere, a thin-walled spherical vacuum chamber (14-inch Ø, 1/16-inch wall thickness) houses the silicon array. The ORRUBA barrel detectors (superX3 detectors from Micron Semiconductor Ltd, which cover ~45° to ~135° in polar angle, with typically 1° resolution) have been augmented with new endcap detectors (QQQ5 detectors from Micron Semiconductor Ltd). These detectors, custom designed for GODDESS to fit inside the superX3 barrel with minimal dead-space, have a graduated strip pitch that provides finer angular resolution at larger angles with respect to the beam axis, where the kinematics for both pickup and stripping reactions are steepest in inverse kinematics. This detector system provides polar angular coverage from ~15° to ~165°, with ~1° polar angular resolution and >70% azimuthal coverage throughout. At backward angles, a single layer of 1000-μm silicon is used throughout the array in its standard configuration. At forward angles, 65-1000-μm telescopes are used in the barrel, and 100-1000-1000-μm telescopes in the forward-angle endcap.

The silicon signals are brought out via a conical chamber in the downstream direction to multi-channel preamplifier boxes, located in the volume vacated by the typically-unused 17° ring of Gammasphere detectors immediately upstream of the first quadrupole magnet of the Fragment Mass Analyzer (FMA). This is the only impact on the Gammasphere configuration. Preamplifiers for up to 720 channels of silicon can be mounted in the standard configuration.

2.3. GODDESS fast ionization chamber

Within the conical chamber, a compact tilted-grid fast ionization chamber (CTGFIC) can be mounted to provide identification and counting of beam particles at rates up to a few 10^5 ions per second, or a coupling can be made to the Fragment Mass Analyzer. Photographs of the compact fast ionization chamber, which is based upon a design built previously at ORNL (K. Y. Chae et al., 2014), is shown in Figure 2. The detector is comprised of grids of 0.0007-inch diameter gold-coated tungsten wire, with a wire spacing of 2 mm and a grid spacing of ~0.5 inch, with each grid tilted to a 30° angle between the grid normal and the beam axis. A total of 21 grids (ten anodes and eleven cathodes) are incorporated in the full detector. Because of the limited space between the GODDESS setup and the first quadrupole of the FMA, the CTGFIC is designed in two parts, allowing the downstream section to be removed, thereby allowing room to extract the upstream section. As signals are brought out of the CTGFIC on the downstream flange, internal connections between the two sections are necessary; these are achieved by means of spring-loaded connectors between the two sections of grids.

Fig. 2. Photo (left panel) of the front half of the compact tilted-grid fast ionization chamber, in which the grids can be seen, and (right panel) photo of the CTGFIC installed in the GODDESS setup, between the preamplifier boxes.

In operation, the CTGFIC is typically filled with CF_4 to pressures between ~10 and ~400 Torr, depending on beam species and energy, and signals read out from the anodes, which can be read out individually, or ganged together in groups via a box that connects to the rear of the CTGFIC. For the tests described herein, the anodes were connected together in two groups, providing energy loss (ΔE) and residual energy (E) signals for simple particle identification using only two chains of electronics. Figure 3 shows a spectrum of ΔE vs E for a beam of ^{134}Xe, incident at ~90,000 ions/second, exhibiting minimal rate-induced signal degradation and pile up. The transmission of each plane of wires is approximately 99.1% (dictated by the ratio of wire diameter to wire spacing). Correspondingly, there is approximately 0.9% transmission loss traversing each grid. Ions which stop prematurely in this manner in one of the residual-energy grids maintain the same ΔE signal as the main beam locus, but carry an E signal that is lowered by discrete amounts corresponding to the energy loss associated with traversing the grid spacing (see Figure 3).

2.4. GODDESS FMA coupling

A system is also incorporated to allow GODDESS to be coupled to the FMA for recoil detection. As the recoil energies for many direct measurements are sufficiently high that they exceed the maximum rigidity for transmission through the FMA, a system of degrader foils is incorporated in this coupling. This system provides up to three foils on a fan-like foil holder, which can be actuated without breaking vacuum, located inside the conical vacuum chamber downstream of the target sphere, in the volume otherwise dedicated to the CTGFIC. The location of these foils was selected as a practical compromise between two opposing factors. On one side, a location as close as possible to the target is preferable (from the point of view of ion optics), to keep the point of divergence from multiple scattering as close to the focal position of the FMA. On the other hand, a location far from the target is preferable to minimize γ-ray backgrounds from interactions of the beam with the degrader foil.

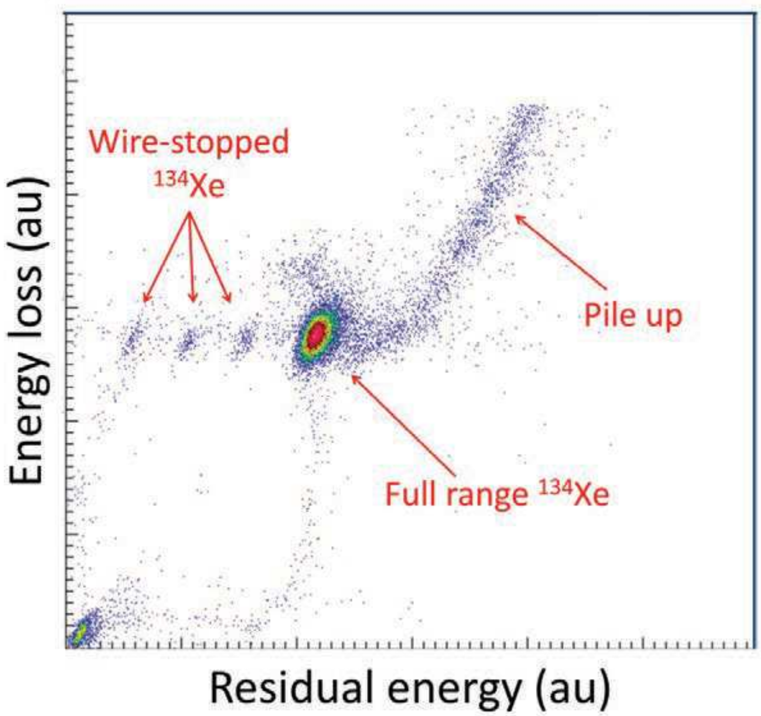


Fig. 3. Particle identification spectrum from the CTGFIC, for incident ^{134}Xe ions at 90,000 ions/second at 10 MeV/A (logarithmic color scale). Events corresponding to ions stopping prematurely by directly impinging on grid wires in the residual-energy region of the detector appear as discretized loci to lower residual energy (see text).

2.5. GODDESS data acquisition

The silicon detector array was split (beam-left and beam-right) across two separate data acquisition systems in order to instrument the large number of silicon electronics channels. Channels were split approximately equally between an analog system of CAEN V785 peak sensing ADCs (ORPHAS), and the digital FMA (DFMA) system of 100-MHz sampling digitizers (J. T. Anderson *et al.* 2012, M. P. Carpenter *et al.* 2015). Digital Gammasphere (i.e. Gammasphere read out with 100-MHz sampling digitizers; DGS) was used for gamma-ray detection. DGS was operated as a slave to the silicon detectors, receiving triggers from both ORPHAS and DFMA, and distributing a clock to the silicon data acquisition systems for time-stamping. Particle singles and particle-gamma coincidences were stored, and events from all three data acquisition systems were merged and sorted off-line.

3. First GODDESS campaign

Three stable beam experiments were carried out in July-September 2015: the GODDESS commissioning experiment ^{134}Xe(d,pγ)^{135}Xe in inverse kinematics, a measurement of the ^{95}Mo(d,pγ)^{96}Mo reaction in inverse kinematics (J. A. Cizewski *et al.*, 2014) in order to demonstrate the feasibility of inverse-kinematic surrogate measurements, and a normal-kinematic measurement of ^{19}F(^{3}He,tγ)^{19}Ne (D. W. Bardayan *et al.*, 2014) to constrain spin assignments in ^{18}Ne for the astrophysically-important ^{18}F(p,α)^{15}O reaction rate in novae. Details of the ^{134}Xe(d,pγ)^{135}Xe experiment and some preliminary data are presented herein.

3.1. ^{134}Xe(d,pγ)^{135}Xe measurement

The ^{134}Xe(d,p)^{135}Xe reaction was measured at 10 MeV/A. In order to simulate performance under radioactive beam conditions, beam intensities ranging from ~10^4 to ~10^8 ions/second were employed, incident on CD_2 targets with thicknesses spanning the range ~200 to ~1000 μg/cm^2. Data shown herein come exclusively from runs using a 765-μg/cm^2 CD_2 target. The GODDESS commissioning experiment is the first measurement of the ^{134}Xe(d,p)^{135}Xe reaction; states based on single-neutron excitations above the N = 82 shell closure (in particular those based on the *f* and *p* orbitals) have not been previously observed in ^{135}Xe.

3.2. Charged-particle singles data

Preliminary charged-particle-singles data from ^{134}Xe(d,p)^{135}Xe at backward angles in the laboratory frame are shown in Figure 4. Kinematic loci (left panel) corresponding to the (d,p) reaction can be seen in the backward angle barrel (95°-130°) and endcap (140°-163°). A preliminary excitation energy spectrum (right panel) gated on two angles (black: ~160°, red: 145°) shows a group corresponding to population of the ground state ($3/2^+$) and first excited state ($1/2^+$) at 288 keV excitation. An energy gap of ~2 MeV can be observed, above which lie states based on the *f* and *p* orbitals above the N=82 shell.

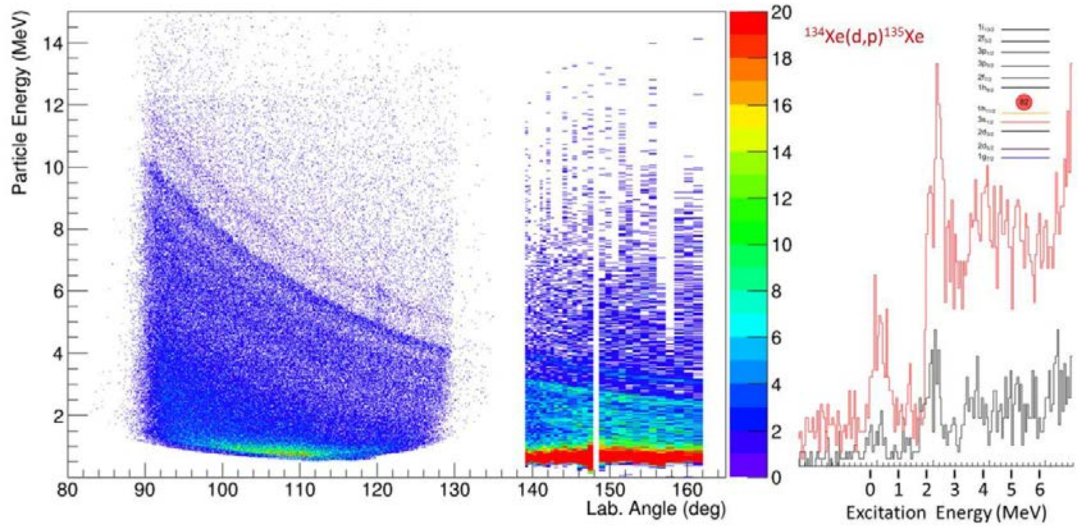


Fig. 4. Preliminary spectrum of particle energy vs laboratory angle (left panel) for upstream GODDESS silicon detectors, showing kinematic loci from the ^{134}Xe(d,p)^{135}Xe reaction. The excitation energy spectra derived from these proton ejectiles are shown in the right panel (black: θ ~160°, red: θ ~145°).

3.3. Particle-gamma coincidences

A particle-gamma coincidence matrix is shown in Figure 5, corresponding only to particle events in the upstream QQQ5 endcap detectors. Excitation energies (as derived from the kinematics of the proton ejectiles) up to the neutron separation energy at 6.36 MeV result in decay by gamma emission from ^{135}Xe. The 288-keV transition can be seen both through direct population of the $1/2^+$ state, and acting as a collecting transition for numerous higher-lying states between ~2 and ~6 MeV. Just above the neutron separation energy, the yield evolves from gammas from ^{135}Xe to gammas from ^{134}Xe, as increased excitation energy results in population of neutron-unbound states, which decay by neutron emission to excited states in ^{134}Xe; the 847-keV $2^+ \rightarrow 0^+$ transition can be seen as the most intense of the ^{134}Xe gamma rays.

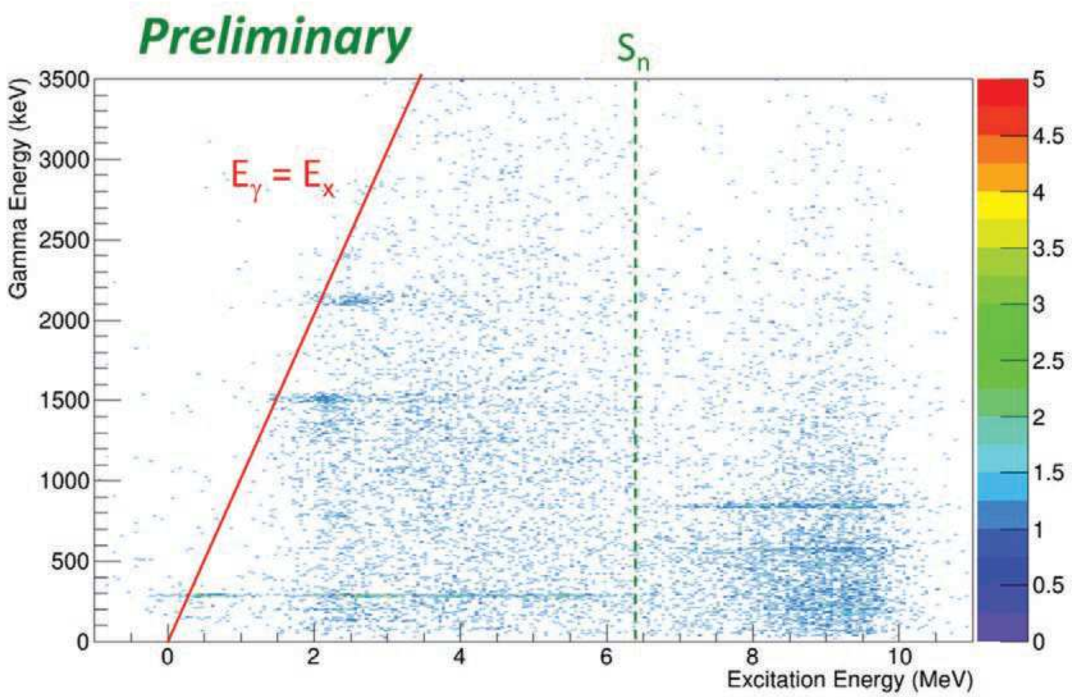


Fig. 5. Matrix of gamma ray energy vs excitation energy as derived from the kinematics of proton ejectiles. The line of equal gamma ray energy and excitation energy is marked; groups on this line correspond to states populated directly in the (d,p) reaction which decay with a single gamma ray to the ground state of ^{135}Xe. The neutron separation energy (S_n) in ^{135}Xe is marked, above which a transition can be observed to the population of states that decay predominantly by neutron emission, resulting in the emission of gamma rays from ^{134}Xe.

4. Conclusion

The GODDESS coupling of ORRUBA silicon detectors and Gammasphere has been successfully completed, and the first campaign of GODDESS measurements with stable beams has been completed. These data are currently under analysis. Three further experiments have been approved using radioactive beams from the CARIBU facility at Argonne National Laboratory.

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