Development of the Oak Ridge Rutgers University Barrel Array

エキゾチック原子核の構造解析用検出器
（オークリッジ・ラトガース式円筒型検出器：ORRUBA）の開発

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Exotic, unstable nuclei play a crucial role in many astrophysical sites, including massive stars and stellar explosions, which contribute to the formation many of the elements found in nature around us. Understanding the properties of these exotic nuclei is critical to understanding these astrophysical sites, and the processes in which elements are synthesized. For decades, one of the major tools for studying the properties of stable nuclei has been the measurement of transfer reactions. A new detector array (ORRUBA: the Oak Ridge Rutgers University Barrel Array) has been developed to perform measurements of transfer reactions using beams of short-lived unstable nuclei, to obtain detailed structure information exotic nuclei. ORRUBA uses a large cylindrical array of resistive-strip silicon detectors to measure transfer reactions with high precision in a cost-effective manner, and has been used for a number of ground-breaking measurements using exotic nuclear beams. By coupling ORRUBA to gamma ray detectors, future measurements will be possible with an order of magnitude greater sensitivity than before.

エキゾチック原子核(不安定かつ短寿命な原子核)は，我々を取り巻く自然界に見られる多くの元素の形成に関係している様々な天体物理学現象，例えば，大質量恒星や恒星爆発において重要な役割を担っている。エキゾチック原子核の性質の把握は，それらの天体物理学現象および元素が合成されるプロセスを理解するうえで不可欠である。この数十年間，安定核種の性質を研究するための有力な手段として，遷移反応の測定が行われてきた。これに対し，我々は，不安定核種であるエキゾチック原子核の詳細な構造情報を入手するため，新しい検出器(ORRUBA)を開発して，エキゾチック原子核ビームを用いた遷移反応測定を行った。ORRUBAでは，一連の反応を高精度に測定するために，複数の板状のシリコン検出器が円筒状に配列されている。費用対効果も高く，エキゾチック原子核ビームを用いた数々の画期的な測定に利用されている。将来的には，ORRUBAとガンマ線検出器を組み合わせることにより，これまでより1桁以上高い感度での測定が可能になると予想される。

Introduction

Stable nuclei, which comprise almost all the material around us (from which we ourselves are made), are an estimated 10% of all possible nuclei which are bound to particle emission (the spontaneous release of a proton, neutron or alpha particle). The remaining ~ 90% are exotic, short-lived isotopes which decay toward the stable isotopes via beta decay. Though these nuclei do not exist long enough to be found commonly on Earth, many play an important role in the synthesis of the elements in stars and explosive stellar environments (such as novae, x-ray bursts and supernovae), decay back to stability, and forming much of the stable material around us.

Understanding these exotic nuclei is crucial to understanding the astrophysical origins of the matter in the Universe.

A cornerstone of our understanding of the structure of stable nuclei has been the measurement of ***transfer reactions***, using beams of light ions (e.g. protons, deuterons, tritons or helium ions) impinged on targets made of the stable nuclei being studied. In a transfer reaction, a nucleon is transferred between the beam nucleus (the ***projectile***), and the target nucleus (***target***), forming a recoil nucleus (the ***recoil***) of similar mass to the target nucleus, and ejecting a light ion similar to the projectile (the ***ejectile***). Such reactions are typically written in the form:

target (projectile, ejectile) recoil.

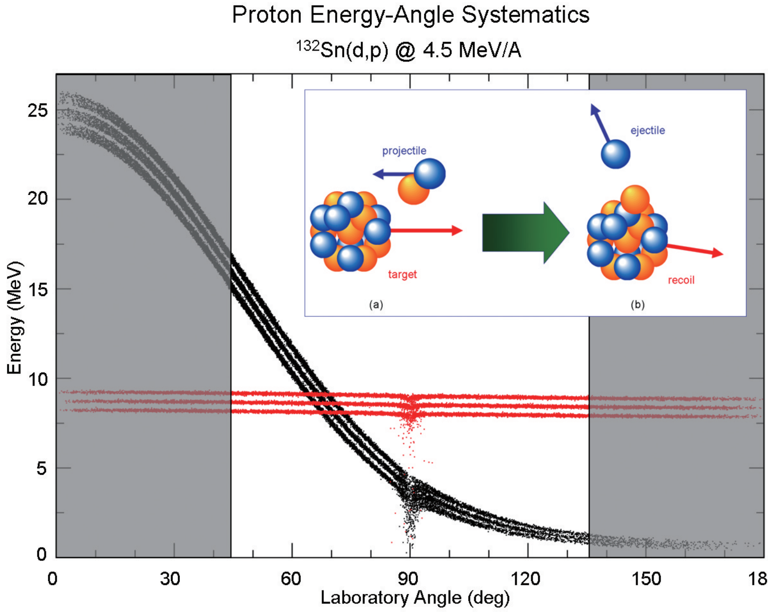

Figure 1 Simulation of the kinematics of the ^{132}Sn (***d, p***) ^{133}Sn reaction, in normal kinematics (red) and inverse kinematics (black) for the equivalent reaction energy (with three fictitious states populated, at 0.0, 0.5 and 1.0 MeV). The region of interest for inverse kinematics is highlighted in white. The effect at 90° is due to energy loss of protons exiting the target at shallow angles. The insert shows a cartoon of the reaction process, in which the deuteron projectile and target nucleus collide (a), transferring a neutron to form a recoil nucleus and a proton ejectile (b).

By measuring the energy and angle of the ejectile from such a reaction, information can be obtained on the nuclear states populated in the recoil. A particularly important reaction is one in which a neutron is transferred from a deuteron to the target nucleus, resulting in a proton ejectile which is measured. The energy of the proton ejected in this transfer reaction (the ***ejectile***) is a direct signature of the energy of the state populated in the recoil nucleus, and the intensity distribution in angle reflects the angular momentum transfer (related to the quantum numbers associated with the nuclear state). Such (***d, p***) reactions favour states in the recoil which have a structural form similar to a single neutron coupled to the target nucleus with low angular momentum, and thus tend to select states which are important for astrophysical reactions. Traditionally, such measurements were performed with a light-ion projectile and a target of the heavy nuclei, and the light ion ejectile was measured in a magnetic spectrograph. This approach is called ***normal kinematics***.

Though transfer reactions have been used for decades to study reactions based on any nucleus that could be made into a target, the vast number of unstable nuclei were out of reach from the technique, as they live for too short a time to be fabricated into a target. However, there has been great progress in the last two decades in the production of rare isotope beams, in which short-lived, unstable nuclei are produced and delivered as a beam. This allows, for the first time, the measurement of transfer reactions on a vast array of these exotic nuclei. Because the heavy nucleus is the beam particle, transfer reactions must be performed in ***inverse kinematics***, in which the light ion is employed as the stationary target in the laboratory. The effect of inverse kinematics is to make the energy of the ejectile highly dependent on angle, rather than almost independent of angle as is the case with normal kinematics. The practical difference is illustrated in Figure 1, which shows the energy of protons emitted from a (***d, p***) reaction, performed in normal (red) and inverse (black) kinematics. In normal kinematics, the energy of the protons for the three states is almost independent of angle. In inverse kinematics, the energy varies rapidly with angle, requiring that the protons are measured with high precision in both energy and angle in order to separate different states.

The nature of the inverse kinematics also results in the interesting region of the proton angular distributions being around $\theta = 90°$ in the laboratory frame. Due to the relatively weak beam intensities obtainable with exotic nuclei, a large acceptance detector is required. Furthermore, for measuring (***d, p***) reactions in inverse kinematics, thin deuterated plastic foils are used as targets. This leads to significant elastic scattering of deuterons and carbon from the target, which cannot be separated from the protons from (***d, p***) by kinematics alone (Figure 2). Therefore, particle identification is critical at angles forward of 90 degrees in the laboratory.

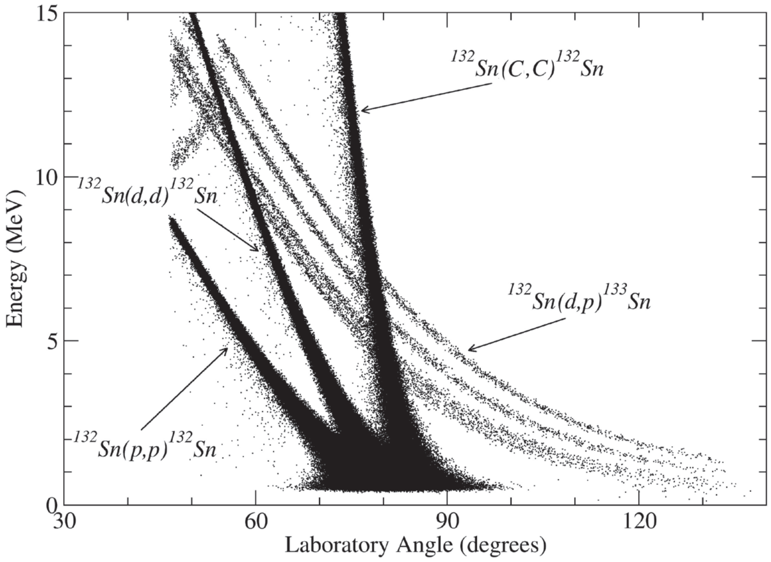

Figure 2 Simulation of the kinematics of the ^{132}Sn (***d, p***) ^{133}Sn reaction, in inverse kinematics. Elastic scattering of carbon (*C, C*) deuterons (*d, d*) and protons (*p, p*) from the target dominate at forward angles, requiring particle identification.

Design of ORRUBA

A new array of silicon detectors, the Oak Ridge Rutgers University Barrel Array (ORRUBA) was constructed to meet the requirements of performing transfer reactions in inverse kinematics, with particular emphasis on the measurement of (***d, p***) reactions.[1] To achieve good position resolution and solid angle coverage, while still maintaining a sufficiently small number of electronics channels (around 300 electronics channels) for instrumentation with existing conventional electronics, resistive-strip silicon detectors were utilized in the array. These detectors measure the position of a detected particle by charge division in the detector, taking a signal from each end of a strip. This is saves an order of magnitude in electronics channels compared to a conventional highly-segmented array, which would require some 2000 to 3000 channels.

The ORRUBA detectors are of custom designs, manufactured by Micron Semiconductor Ltd, with an active area 7.5 cm × 4.0 cm. The non-resistive design, utilized in the ΔE layer of the forward angle ring, is divided into eight strips of 7.5 × 0.5 cm. The resistive strip detectors are divided into four strips of 7.5 × 1 cm, with readout from both ends of each strip for position and energy determination. At a radial distance from target to detector plane of ~ 8 cm, the maximum uncertainty in polar angle due to the strip width is < 0.5 degrees, even though the azimuthal range per strip is up to 7.2 degrees.

The entire array consists of two rings of silicon detectors, as illustrated schematically and in the photograph in Figure 3, designed to operate typically with one ring forward and one backward of $\theta = 90°$. The forward angle ring consists of ***detector telescopes*** - a thin detector backed by a thick detector - to provide particle identification via standard energy-loss techniques. These telescopes are comprised of 65-µm-thick non-resistive strip silicon detectors for ΔE measurement, and position-sensitive 1000-µm-thick resistive-strip detectors are employed as stopping detectors. The backward angle ring is comprised of a single layer of 500-µm-thick resistive strip detectors. In its standard configuration, the array gives approximately 80% coverage in azimuthal angle

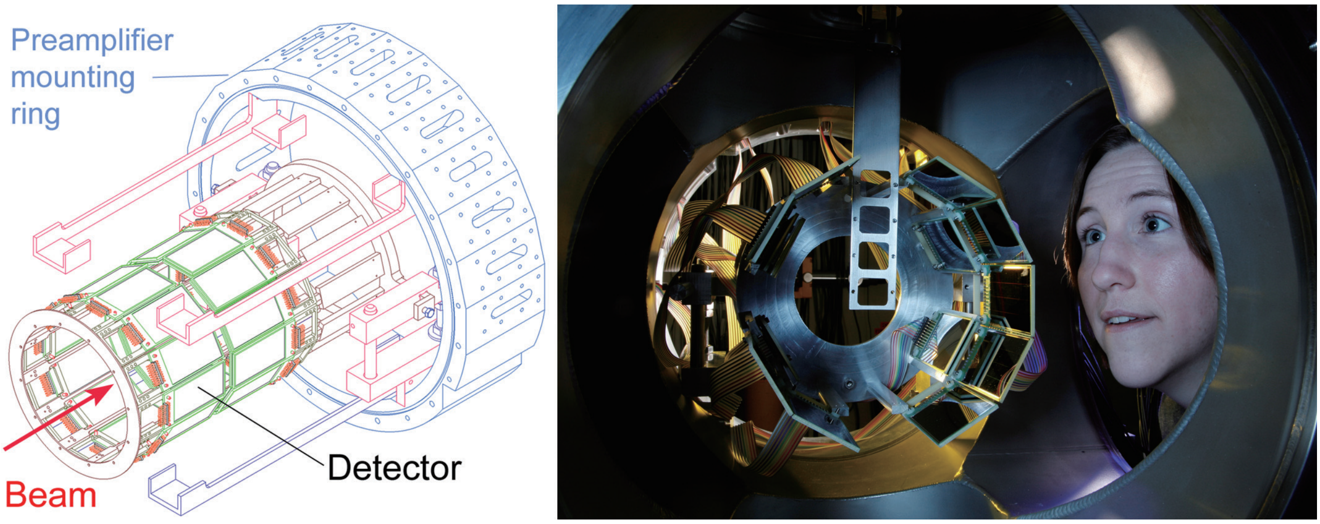

Figure 3 A schematic drawing (left) and photograph (right) of ORRUBA, showing the two rings of silicon detectors in a barrel arrangement. The direction of the beam is indicated by the red arrow.

over the polar (θ) angular range ~ 45° to ~ 135°.

Detector Performance

Evaluation of the performance of resistive ORRUBA detectors was achieved utilizing proton beams from the tandem accelerator at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory. ORRUBA detectors were mounted downstream of a 100 $\mu g/cm^2$ gold target, subtending angles between $\theta \approx 10°$ and 30°, thus illuminating the detectors with nearly mono-energetic elastically scattered protons. The energy of the scattered protons was varied by altering the beam energy, enabling the depletion depth of the detectors to be probed, along with the energy dependence of the energy and position resolutions. The performance in position measurement was determined by placing a mask with a series of precision slots, of known width and spacing, immediately in front of the detectors. Measurements of 11.5 MeV protons yielded a position resolution of approximately 0.5 mm (FWHM) , and an energy resolution of typically <60 keV (FWHM). The non-resistive detectors showed an energy resolution of ~ 100 keV.

Measurements using ORRUBA

ORRUBA has been critical to multiple experiments with beams of exotic nuclei since its commissioning. Among these are ^{132}Sn (***d, p***) ^{133}Sn, ^{130}Sn (***d, p***) ^{131}Sn, ^{134}Te (***d, p***) ^{135}Te, ^{10}Be (***d, p***) ^{11}Be, ^{26}Al (***d, p***) ^{27}Al and ^{132}Sn (***d, t***) ^{131}Sn. By measuring transfer reactions on these exotic nuclei (many of which, as previously mentioned, are important for understanding the astrophysical origins of the elements), the single-particle nature of their nuclear structure can be probed. This structure is important for constraining nuclear models, and for providing information about neutron-capture cross sections important for astrophysics in such scenarios as supernovae or neutron star mergers. The measurements can even inform proton-capture reactions important to novae and x-ray bursts, due to the mirror symmetry of proton and neutron states.

One specific example of such measurements was an experiment into the nuclear structure of the exotic nucleus ^{132}Sn. This particular isotope of tin is intriguing because it has 50 protons and 82 neutrons, both of which are nuclear “magic numbers”, meaning that they correspond to closed nuclear shells in nuclei close to stability. Stable nuclei with such magic numbers of protons or neutrons exhibit properties such as having a characteristically spherical structure, requiring a particularly large amount of energy to excite them from their lowest energy state, and a comparatively loose binding of further nucleons added to them. Though ^{132}Sn is a “doubly magic” nucleus, it is also an exotic neutron-rich nucleus, and such magic numbers have been observed to break down (and new magic numbers appear) in exotic neutron-rich nuclei. The ^{132}Sn (***d, p***) ^{133}Sn measurement was performed in order to determine to what extent this magicity is retained in this exotic, neutron-rich unstable nucleus. The ^{132}Sn (***d, p***) ^{133}Sn reaction transfers one neutron onto ^{132}Sn, allowing the examination of the behaviour of ^{133}Sn’s nuclear structure. The results of this study were recently published in Nature.[2] (Figure 4) This experiment showed that the states in ^{133}Sn have properties almost completely dominated by the properties of the single neutron added to ^{132}Sn, indicating that ^{132}Sn is the heaviest, most neutron-rich doubly-magic nucleus ever studied.

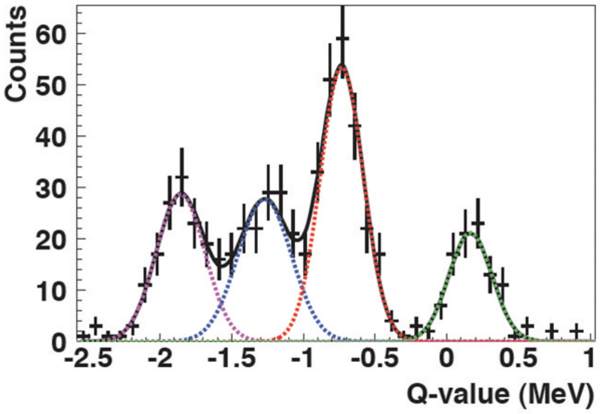

Figure 4 Four states in ^{133}Sn populated via the ^{132}Sn (***d, p***) ^{133}Sn reaction measured using ORRUBA.[2] These levels exhibit strong single-particle properties, indicating the highly magic nature of ^{132}Sn.

The Future - ORRUBA coupled to arrays of gamma-ray detectors

Because of the flexible, compact design of ORRUBA, it is ideally suited to merging with other detector arrays in order to improve its resolving power. A particularly promising technique for improving the measurement of transfer reactions is to measure gamma rays from the decay of exited states populated in the transfer reaction. Such gamma rays can be measured with even higher precision than the charged particle *ejectiles*, and provide important complementary information on the nuclear states populated and the way in which they decay. To this end, ORRUBA is currently being coupled to the Gammasphere array of germanium detectors - one of the most powerful gamma-ray detectors arrays in the world. This will improve the resolving power of ORRUBA by about an order of magnitude, along with multiple other

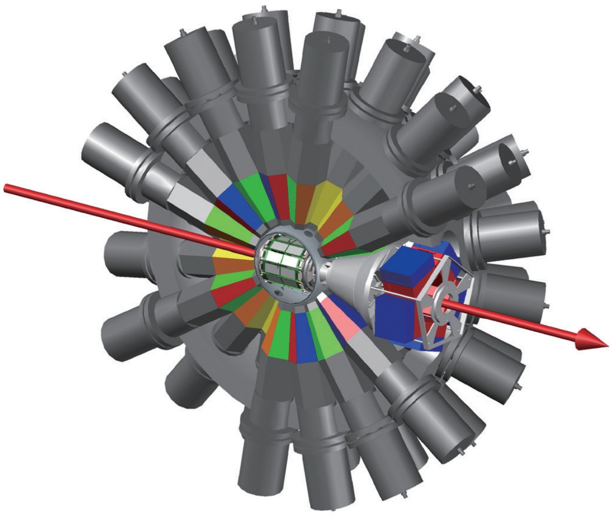

Figure 5 A 3-dimensional design drawing of the coupling between ORRUBA and Gammasphere, showing the two rings of silicon detectors at the center of the Gammasphere gamma-ray detector array. Electronics are mounted in close proximity downstream of the array; the direction of the beam is indicated by the red arrow.

benefits from the information from the gamma rays. An image of the 3D design drawings for the coupling is shown in Figure 5, in which ORRUBA is visible at the center of the radial array of Gammasphere detectors. Electronics for ORRUBA are mounted in the tight confines of the downstream end of the system (beam direction being indicated by the red arrow) to maximize their proximity to the detectors.

Summary

An array of silicon detectors has been developed for the measurement of ejectiles from transfer reactions in inverse kinematics, utilizing resistive-strip silicon detectors for precise measurement of the emission angle and energy of ejectiles. Particle identification is achieved with detector telescopes, comprised of 65- μm-thick non-resistive ΔE detectors, backed by thick resistive-strip detectors. The entire array has a total channel count which can be instrumented using conventional electronics. The array has been utilized in the first measurement of the ^{132}Sn (***d, p***) ^{133}Sn reaction, leading to experimental evidence of the highly doubly-magic nature of the ^{132}Sn nucleus. Other experiments have studied single-neutron states in ^{131}Sn (important for understanding the formation of the heavy elements in the supernovae and merging neutron stars), for studying the exotic neutron halo of ^{11}Be, and for constraining the destruction rate of ^{26}Al in giant stars. ORRUBA is currently being coupled to the Gammasphere array of gamma detectors, which will increase the sensitivity of such measurements by an order of magnitude.

References

[1] S.D. Pain, et al., Development of a High Solid-Angle Silicon Detector Array for Measurement of Transfer Reactions in Inverse Kinematics, *Nucl. Instr. Meth.*, **B 261** (2007) 1122

[2] K.L. Jones, et al., The magic nature of ^{132}Sn explored through the single-particle states of ^{133}Sn, *Nature* **465** (2010) 454

[3] I.-Y. Lee et al., The GAMMASPHERE, *Nucl. Phys.*, **A 520**, 641c (1990)

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