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Recent advances in β-decay spectroscopy at CARIBU

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Abstract. β-decay spectroscopy of nuclei far from stability can provide powerful insight into a broad variety of topics in nuclear science, ranging from exotic nuclear structure phenomena, stellar nucleosynthesis processes, and applied topics such as quantifying “decay heat” discrepancies for advanced nuclear fuel cycles. Neutron-rich nuclei approaching the drip-line are difficult to access experimentally, leaving many key examples largely under studied. The CARIBU radioactive beam facility at Argonne National Laboratory exploits spontaneous fission of ^{252}Cf in production of such beams. The X-Array and SATURN decay station have been commissioned to perform detailed decay spectroscopy of low-energy CARIBU beams. An extended science campaign was started during 2015; with projects investigating nuclear shape changes, collective octupole vibrations, β-delayed neutron emission, and decay-scheme properties which could explain the reactor antineutrino puzzle. In this article we review the current status of the setup, update on the first results and recent hardware upgrades, and look forward to future possibilities.

1 Introduction

In recent years, significant effort in experimental nuclear physics has been expanded to access more and more exotic regions of the nuclear chart lying far from stability. The greatest hindrance to such experiments is the diminutive production cross sections associated with radioactive ion beams (RIBs). One method to circumvent this issue is to build highly-efficient experimental setups, capable of detecting as many of these rare events as possible.

Neutron-rich nuclei with $100 < A < 160$ present an interesting region with regard to a broad range of topics in nuclear-physics research. For example, ^{132}Sn is often discussed as an example of a doubly-magic nucleus [1]. Studies performed on its neighbouring nuclides can offer detailed insight into single-particle excitations and proton-neutron interactions with large core neutron excesses. Dramatic ground-state shape changes due to collective motion are known to occur in the neutron-rich $A \sim 100$ region [2]. Many of the most interesting cases happen to be refractory elements, which are notoriously difficult to access through conventional RIB-production methods. The path of the *r*-process is also predicted to lie within this area [3]. Nuclear ground-state and isomer masses and decay half-lives are central to *r*-process and elemental abundance calculations, with sensitivity studies highlighting the need for more accurate measurements to be performed (e.g. Ref. [4]). The region also incorporates products of the fission process, which is pertinent to the understanding of decay heat in advanced fuel cycle processes [5] and the so-called ‘antineutrino anomaly’ [6].

The most direct route to accessing neutron-rich RIBs is through the fission of heavy nuclei. The CAlifornium Rare Ion Breeder Upgrade (CARIBU) is a RIB facility located at Argonne National Laboratory [7]. At the heart of the CARIBU system is a ~1-Ci ^{252}Cf source. This nucleus primarily α decays with a half-life of approximately 2.6 years. However, it also possesses a spontaneous fission branch of about 3% which is exploited by CARIBU.

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Since ^{252}Cf possesses greater A and Z than other actinides typically used in ISOL-based facilities, such as proton- or neutron-induced fission of ^{235}U, CARIBU beams have the potential to access unique regions of the nuclear landscape. There is also the added benefit of greatly-enhanced refractory element extraction from the ^{252}Cf fission source.

Fission fragments extracted from the source are thermalised in a gas catcher that was developed at Argonne. Here, they are slowed in high-purity helium gas, and a combination of DC and RF fields focus them into a low-emittance beam. The species of interest is selected in the isobar separator, where it is either sent for charge breeding and acceleration through the ATLAS facility, or directed to the low-energy experimental area. A new β-decay spectroscopy station has been built for use with low-energy CARIBU beams. The first dedicated experimental campaign to be conducted with the new setup is the focus of this article.

2 First results

The decay station consists of two main components. The X-Array is a highly efficient array of five High-Purity Ge clover detectors mounted on an adjustable frame. The frame itself was designed to provide flexibility, enabling the clovers to be easily positioned or removed as necessary to accommodate auxiliary detectors. Large clover crystals located in close proximity to the collection point result in a high γ-ray detection efficiency of $\sim$12% at 1 MeV. Utilising the 'add-back' capabilities of the clovers increases the measured peak-to-total ratio by reconstructing events that are scattered between crystals, thereby improving photopeak efficiency and reducing the Compton background. The second component is SATURN, a tape-transport system for removal of long-lived activity with plastic scintillators surrounding the collection point for detection of β particles. A full description of the decay station can be found in Ref. [8].

Commissioning of the decay station was completed in 2014 [9]. Much of the early work was conducted with beams of neutron-rich Cs isotopes. Chemistry of this region enables excellent m/q selection for Cs ions as they favour extraction in a 1^+ charge state from the gas catcher, whereas the neighbouring isobars favour a 2^+ charge state. Results from the ^{146}Cs β-decay experiments have recently been published [10].

3 Recent developments

The first extended low-energy decay campaign took place in 2015. One of the experiments we performed was focused on the $A = 100$ region which is well known for dramatic shape changes. The Sr and Zr isotopes undergo a dramatic change from vibrational to rotational character between $N = 58$ and $N = 60$. However, with just two protons more, the Mo isotopes are seen to undergo a more gradual shape transition. The heaviest Mo isotopes exhibit some of the lowest 2^+_2 energies measured, suggesting the existence of triaxial deformation, for which accurate γ- to ground-state-band branching ratios are desirable.

However, these nuclei are difficult to access experimentally due to their exotic and refractory nature. High-spin band structures have been observed from prompt-fission studies, whereas little is known about collective structures at low spin and excitation. β decay of Nb is an ideal probe of the low-energy structure of Mo. Detailed data sets of ^{104,106}Nb $\rightarrow$ ^{104,106}Mo β decay were taken for five days and are currently under analysis. A sample of the data for ^{104}Mo is presented in Fig. 1. The spectrum shows a projection of the $\beta - \gamma - \gamma$ coincidence matrix, gated on the 620-keV γ-ray transition connecting the $2^+_\gamma \rightarrow 2^+_{\mathrm{gs}}$ levels. A partial level scheme has been constructed using this information and is also shown. Spins and parities quoted here are taken from Ref. [11]. The ground state of ^{104}Nb is tentatively assigned $J^\pi = (1^+)$ in the literature. Strong population of the high-spin states that would be highly forbidden in β decay from the low-spin ground state is due to the occurrence of a β-decaying isomer in the parent which must have $J \approx 5$.

Each recorded event is timestamped relative to the beginning of a predetermined time cycle. The cycling used for the ^{104}Nb decay experiment consisted of 10-s beam-on/beam-off intervals to study the ground-state and isomer decay with half-lives of 0.94(4) s and 4.9(3) s, respectively [11]. The growth-and-decay curve for the 368-keV β-gated γ-ray transition ($4^+_{\mathrm{gs}} \rightarrow 2^+_{\mathrm{gs}}$) is shown in Fig. 2. Since a $1^+ \rightarrow 4^+$ β decay is second forbidden, the 4^+ levels in ^{104}Mo must be predominantly populated by the isomer decay. By fitting an exponential decay plus linear background function to the 'decay' portion of the curve, a half life of 0.97(1) s was extracted for the isomer from these data. This is in excellent agreement with the adopted value of 0.94(4) [11].

During this campaign, auxiliary detectors were installed on the X-Array, in place of one of the clovers, for the first time. Five LaBr$_3$(Ce) detectors were installed for two of the experiments with the aim of measuring excited-state lifetimes shorter than 100 ps. An array of 16 Cs$_2$LiYCl$_6$:Ce (CLYC) scintillator detectors, built by the University of Massachusetts Lowell, was also commissioned during the campaign. Conventional CLYC scintillators perform as γ-ray spectrometers with good energy resolution, but also as thermal neutron detectors, via the ^{6}Li(n, α) reaction, as they offer excellent pulse-shape discrimination [12]. They have also been found to be sensitive to fast neutrons via the ^{35}Cl(n, p) reaction. In the Lowell array, the thermal neutron response is suppressed by depleting the ^{6}Li content [13]. This makes them ideal for studying fission neutrons and β-delayed neutron emission with neutron-rich CARIBU beams.

In total, seven experiments investigating a broad range of topics across nuclear-reactor physics, β-delayed neutron emission, nuclear octupole vibrations and shape coexistence were performed during the campaign, which spanned 28 days of low-energy beam time. Analyses of the data are ongoing, and we are excited about the prospect of results the campaign may yield in the near future.

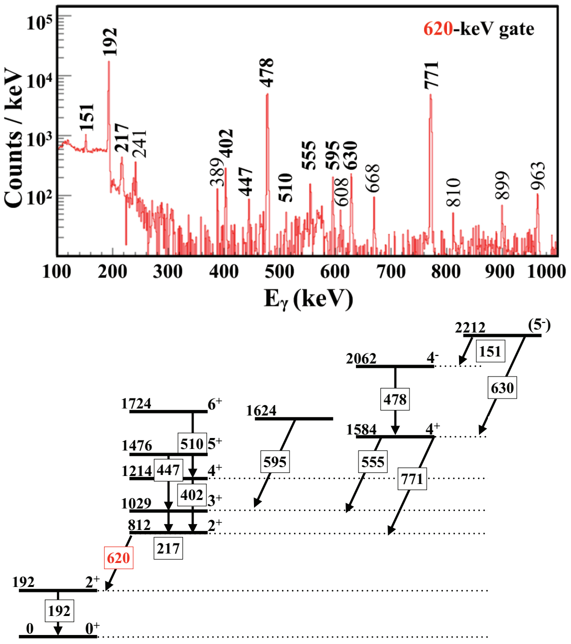

Figure 1. [Colour online] (Top) Projection of the $\beta-\gamma-\gamma$ coincidence matrix gated on the 620-keV γ-ray transition in ^{104}Mo. (Bottom) Partial level scheme (not to scale) constructed from the 620-keV γ-ray gate. The γ rays included in the level scheme are labelled in bold in the spectrum. The other labelled γ rays are weak branches that have not been included in this level scheme. Spins and parities of the levels included here are from Ref. [11].

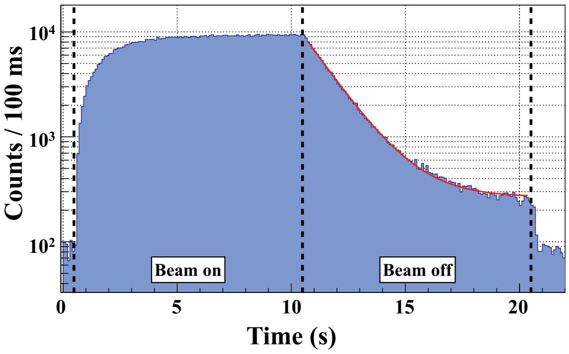

Figure 2. [Colour online] Example of a growth-and-decay curve for the time cycle described in the text. These data are for the 368-keV β-gated γ-ray transition in ^{104}Mo.

4 Outlook

A number of additional measurements have been performed since the initial campaign. The majority of these have been with beam species with the largest fission yields. Two issues for subsequent experiments that aim to study weaker beams are the isolation of the isotope of interest from the neighbouring isobars and the backgrounds induced by radiation from the CARIBU source. A new MR-TOF separator has been installed on the low-energy beamline. This enables much more effective mass separation which is crucial for studies of exotic isotopes. The next stage of experiments will involve relocating the low-energy experiments to the adjacent hall which used to house the tandem injector. This will be a significant undertaking, and will require construction of new beam lines and other infrastructure. The benefits after this work is completed should be significant, opening up possibilities to study nuclei pushing out closer to the neutron drip line.

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