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Novel Approach to β-Delayed Neutron Spectroscopy

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Characterizing β-delayed neutron emission (βn) is of importance to reactor safety modeling, r-process nucleosynthesis calculations, and nuclear structure studies. A newly developed recoil-ion detection technique avoids the difficulties associated with direct neutron detection, enabling precise measurements of βn branching ratios and neutron energy spectra. Ions of interest are studied using the Beta-decay Paul Trap (BPT), an open-geometry ion trap surrounded by an array of radiation detectors. The neutron energy can be determined from the recoil imparted to the detected ions following βn decay. Branching ratios are deduced by detecting β particles, γ rays, and ions. The apparatus was used in a recent experimental campaign at the CARIBU facility at ANL to collect high-quality data on the β decay of trapped $^{137-138,140}$I, $^{144-145}$Cs, and $^{134-136}$Sb ions.

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1. Introduction

For decays of neutron-rich nuclei where β^- decay populates excitation energies above the neutron separation energy, the daughter nucleus may de-excite via neutron emission, in a process referred to as β-delayed neutron emission (βn). This decay mode influences elemental abundances calculated in the astrophysical r-process nucleosynthesis models [1]. Precise measurements of βn branching ratios (P_n) and neutron energy spectra are also necessary for safety analysis calculations of novel reactor designs [2], and can illuminate aspects of nuclear structure in studies of neutron-rich nuclei [3]. In addition, high-quality βn data provides constraints needed for modern nuclear-structure calculations and empirical models [4–6] that are used to predict decay properties of nuclei for which no data exist. Despite these important applications, existing data for neutron-rich nuclei are often incomplete or discrepant [7, 8], motivating the use of additional experimental approaches such as the recoil-ion technique to extract precise branching ratios and neutron energy spectra [9].

2. Experimental Method

Neutron-rich isotopes are loaded into the Beta-decay Paul Trap (BPT) [10], a linear radiofrequency quadrupole trap, surrounded by two plastic scintillator detectors each in a ΔE-E configuration for detecting β particles, two position-sensitive microchannel plate (MCP) detectors for detecting recoiling ions, and two high-purity germanium (HPGe) detectors for γ-ray spectroscopy. A schematic of the trap and detector geometry is shown in Fig. 1 and the detectors are described in more detail in Ref. [11]. The time difference between the β-particle detection and the recoil-ion detection determines the time-of-flight (TOF) of the ion, and hence the recoil energy imparted by the decay. Using conservation of momentum, the neutron energy can be obtained from the nuclear recoil if the small contribution from the lepton and γ-ray emission is neglected. In the case of β decay without neutron emission, the ion's recoil energy is typically ~100 eV. These recoils arrive at the MCP detector with longer TOFs than the recoils characteristic of βn emission, which can have energies that extend above 10 keV. The branching ratios can be deduced using three methods by comparing the number of ions with short TOFs (associated with neutron emission) to (1) the number of ions with longer TOFs, (2) the number of $\beta - \gamma$ coincidences deduced from the γ peaks, and (3) the number of β particles from the trapped species of interest detected using the plastic scintillator detectors. Comparison of the resulting branching ratios established with these three methods provides checks that systematic uncertainties are properly taken into account.

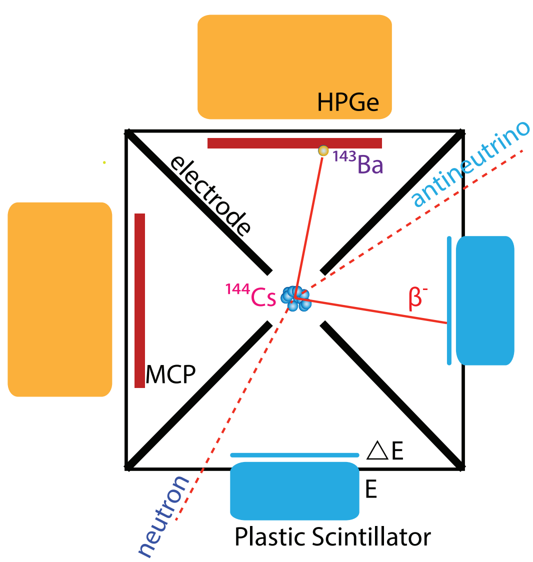

Fig. 1. Schematic of the cross-sectional end view of the BPT experimental setup (not to scale), using the βn decay of ^{144}Cs as an example.

3. Preliminary Analysis

During the experimental campaign in late 2013, the BPT was installed on a low-energy beamline at the CAlifornium Rare Isotope Breeder Upgrade (CARIBU) facility at Argonne National Laboratory [12]. At the CARIBU facility, the spontaneous fission of ^{252}Cf supplies fission products, and the isotope of interest is selected using a high-resolution magnetic isobar separator. A radiofrequency quadrupole buncher then accumulates and bunches the ions for delivery to the BPT. The beam intensities at CARIBU were much higher than had been available during previous BPT experimental campaigns (that used a ~1-mCi ^{252}Cf source and the system described in [9]) and allowed high-quality data to be collected on $^{137-138,140}$I, $^{144-145}$Cs, and $^{134-136}$Sb. The initial analysis has focused on interpreting the ^{137}I and ^{134}Sb decay data. The simplicity of the ^{134}Sb ground state β decay (which predominantly directly populates the ground state of the daughter ^{134}Te nucleus) allows it to serve as a calibration of the MCP detection efficiency and a verification of the simulations and analysis procedures. For ^{137}I, the recoil-ion TOF spectrum is shown in Fig. 2 and is consistent with previous measurements made with the BPT [9]. The three P_n measurement methods yield branching ratios that agree with existing results [13] to within the currently estimated uncertainty of the measurements, which is ~15%. The ongoing analysis aims to reduce these uncertainties by better characterizing the performance of the detector array and precisely determining a variety of systematic effects using detailed simulations of the β decay and experimental system.

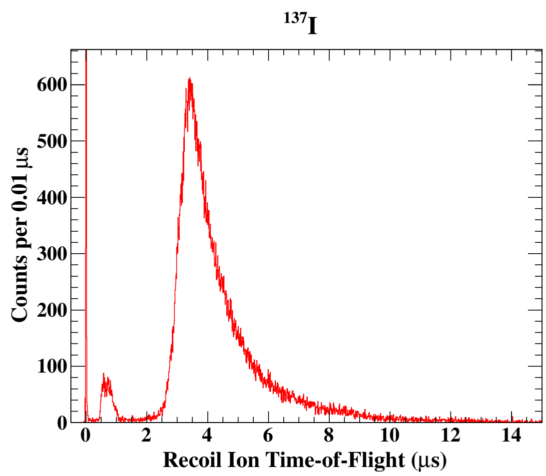

Fig. 2. Time-of-flight spectrum of recoil ions following ^{137}I β decay. Ions at short TOF's (between approximately 0.4 and 1.5 μs) are characteristic of βn emission resulting in ^{136}Xe ions, while ions at longer TOF's (above 2 μs) result predominantly from β decay to the ground state and γ-ray emitting states in ^{137}Xe. The sharp peak near zero TOF is due to coincidences in which the MCP is triggered by scattered β particles and/or γ rays.

4. Future Plans

Plans for upgrades to the experimental setup consist of expansion of the detector array to increase the detection solid angle, and enhancements to the trap to improve ion collection and cooling while minimizing the effect of the electric fields on the recoiling ions. Future experiments will also benefit from anticipated increases in the intensity and purity of the low-energy beams delivered by the CARIBU facility in the coming years. These improvements will allow experiments to probe further into the neutron-rich region.

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