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PROBING EXCITED STATES IN NUCLEI AT AND BEYOND THE PROTON DRIP-LINE*

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The coupling of a Compton-suppressed Ge (CSGe) detector array to a recoil separator has seen limited use in the past due to the low efficiency for measuring recoil-γ ray coincidences ($< 0.1\%$). With the building of new generation recoil separators and gamma-ray arrays, a substantial increase in detection efficiency has been achieved. This allows for the opportunity to measure excited states in nuclei with cross-sections below 100 nb. In this paper, results from the coupling of a modest array of CSGe detectors (AYE-Ball) and a current generation Ge array (Gammasphere) with a recoil separator (FMA) will be presented.

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1. Introduction

The study of nuclei far from stability has received much attention recently. Indeed, the thrust of the next generation radioactive beam facilities will be to study neutron rich nuclei. However, it is doubtful that the next generation RIB facilities will push all the way to the neutron-drip line except for the lightest elements. On the other hand, nuclei which lie at and beyond the proton-drip have been produced and identified for elements as heavy as Bismuth ($Z = 83$) using either heavy-ion induced fusion evaporation reactions with stable beams and targets or multi-fragmentation reactions. Until recently, many of these isotopes were characterized solely by their decay properties and lifetimes, and little, if anything, was known about their excited states.

This situation has changed somewhat in the last several years with the coupling of modest and large gamma-ray arrays to other detection systems which allow for the isolation of weak channels and their associated γ rays

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from stronger sources of γ radiation, *e.g.* other residue channels, fission, and Coulomb excitation. Presently, two general techniques are used in γ-ray spectroscopic studies to make isotopic identification of weak channels produced in fusion-evaporation reactions. The first involves the measurement of evaporated particles, *i.e.* neutrons, protons, and/or α particles. The number and type of particles measured give some degree of nuclide identification. The second technique directly detects the residue using either a recoil separator or a recoil detector. Isotopic identification is made by measuring the properties of the residue, *i.e.* mass, energy, time of flight, and/or decay products. In this contribution, the discussion will focus on studies of excited states in nuclei utilizing the second technique. Specifically, results from γ-ray spectroscopy experiments using gamma-ray arrays coupled to a high resolution recoil mass spectrometer will be presented.

2. The recoil decay tagging technique

A high resolution recoil mass separator is installed on a beam line of the heavy-ion accelerator, ATLAS, at Argonne National Laboratory. This device, named the Fragment Mass Analyzer (FMA), is an 8.2-meter-long mass spectrometer which separates reaction products produced in a heavy-ion fusion reaction and disperses then by Mass/Charge (M/Q) at the focal plane [1]. While the focal-plane detector offers M/Q separation typically of 350:1, it does not provide isotopic (Z) information. Z information is obtained at the FMA by placing ancillary detectors behind the focal-plane. For light and medium mass nuclei ($Z < 50$), it is possible to obtain Z-separation by using an ionization chamber, however, this technique does not work for heavier nuclei.

A technique for isotopic identification of γ rays which is applicable to heavy nuclei far from stability has been developed recently, and it is commonly referred to as Recoil Decay Tagging (RDT). Isotopic identification is made by correlating the characteristic charged-particle radioactivity of an ion implanted in a pixel of a double-sided silicon strip detector (DSSD) with a previously implanted recoil. Fig. 1 shows schematically how the technique works utilizing the DSSD setup at the FMA. Above the closed proton shell at $Z = 50$, many nuclei near the proton-drip line decay by the emission of an α particle. Beyond the drip line, odd-Z nuclides are observed to decay by proton emission, and they too are excellent candidates for RDT studies.

RDT is an extremely sensitive technique, and γ rays have been identified in channels produced with cross-section as low as 50 nb. While the technique is quite sensitive, this comes with a cost. Using a device such as the FMA, only about 5–15% of the recoils produced at the target are detected at the focal plane. In addition, only 1/2 of the decay products deposit their full