Study of Excited States in Nuclei at the Proton Drip-Line using Proton-Rich Radioactive Beams

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While much of the experimental program for the RIA facility will be directed at the study of neutron rich nuclei, enhancing our understanding of nuclear structure at the limits of stability on the proton rich side will also be possible. This writeup will concentrate on the potential to use proton-rich radioactive beams to produce nuclei at the proton-drip line via heavy-ion fusion evaporation reactions.

Heavy-Ion Fusion Evaporation

While the use of neutron-rich beams in heavy-ion fusion reactions will allow us to produce neutron-rich compound systems, the reduced neutron binding energies will result in an increase in the number of evaporated neutrons from the compound system with respect to stable or proton-rich nuclei. For example, a ^{140}Sn beam incident onto a ^{48}Ca target leads to the neutron-rich compound nucleus, ^{188}Yb. Unfortunately, once the systems fuse, the excitation energy results in an evaporation of seven neutrons. The 7n channel, ^{181}Yb, lies only 5 neutrons away from stability (^{176}Yb). As a result, other types of reactions such as Coloumb excitation and deep-inelastic reactions will most likely be utilized to study excited states in the most neutron rich nuclides.

In contrast, heavy-ion fusion reactions using stable target and beam combinations are used to probe excited states in nuclei lying at the limits of stability on the proton-rich side of the nuclear chart. The use of radioactive beams will greatly ehance our ability to study these systems by allowing for significant increases in production cross-sections.

N=Z nuclei from Ni to Sn

The N=Z nuclei between Z=28 and Z=50 closely follow the proton-drip line, and offer a particularly interesting laboratory for nuclear structure studies. These nuclei are also of interest in nuclear astrophysics due to the fact that the r-p process is predicted to follow closely the N=Z line.

Nuclear structure issues associated with the the N=Z symmetry include measuring and quantifying the decline of isospin purity and determining the importance of T=0 and 1 n-p pairing. In addition, the single-particle spectrum for these particle numbers show many large energy gaps at various deformations. The N=Z symmetry reinforces these gaps, resulting in predictions of large shape changes and shape coexistence for these nuclei. Finally, the region around the doubly magic nucleus ^{100}Sn is also extremely interesting from a nuclear structure aspect, because it affords one the opportunity to test shell model calculations at the limits of proton binding.

Gamma-ray spectroscopic studies of these nuclei have been going on for many years. With the coupling of the large gamma-ray arrays to ancillary particle detectors, progress is being made in studying excited states in N=Z systems. Some of our resent results from Gammasphere show anomalies in the high-spin behavior. Whether these anomalies are related to for example n-p pairing is not clear and more detailed information is needed. Enhanced production cross sections obtained by using reactions with proton-rich radioactive beams will provide this information.

As an example, the heaviest N=Z nucleus studied with Gammasphere was ^{88}Ru using the ^{32}S(^{58}Ni,2n)^{88}Ru reaction. One hopes to be able to identify the first few excited states in this nucleus from the current data set. An alternative reaction using a radioactive beam would be ^{40}Ca(^{56}Ni,2α)^{88}Ru. From the compilation, the intensity of the ^{56}Ni beam would be 1pnA. *Note: need estimates for increase in cross-section.* This increased cross-section should allow a more detailed study of this N=Z nucleus and similar use of radioactive beams should open up studies of the N=Z systems all the way to ^{100}Sn.

Studies Beyond the Proton Dripline from Sn to Pb

Above Z=50, the limits of proton excess are defined by the proton emitters which have been identified in odd-Z nuclei up to Bismuth (Z=83). These nuclei lie beyond the proton drip line and are kept bound by the Coulomb force. The lifetimes in many of these cases can be well reproduced by WKB calculations using spectroscopic factors derived from spherical shell model calculations. This allows for definitive single-particle assignments to be given to the proton-emitting states. Recently, proton radioactivity has been observed in ^{141}Ho and ^{131}Eu. However, the decay lifetimes cannot be reproduced by WKB calculations, and this has been interpreted as evidence for deformed grounds states in these nuclei. By studying excited states built on top of these proton emitters, one should be able to independently confirm both the deformation and single-particle parentage of the proton-emitting state. Other questions which can be addressed by studying excited states in nuclei lying beyond the drip-line include:

- Do present models whose parameters have been adjusted using stable nuclei reproduce adequately nuclear structure all the way to the limits of stability, including deformations, single-particle energies, and the evolution of structure as a function of angular momentum?
- How much excitation energy and angular momentum can these quasi-bound systems accommodate?
- Is there any evidence of mixing between bound and unbound states is these loosely bound systems? For example, a substantial increase in pairing might occur as the bound states mix with the unbound continuum.

We have performed a gamma-spectroscopy measurement on the deformed proton emitter ^{141}Ho using Gammasphere. The ^{92}Mo(^{54}Fe,p4n)^{141}Ho reaction was used yielding a production cross-section of only $\sim$ 300nb (for the case of ^{131}Eu the production cross-ection is even lower). An alternative reaction using a radioactive beam would be ^{54}Fe(^{89}Mo,pn)^{141}Ho. From the compliation, the intensity of the ^{89}Mo beam would be 1pnA. For this alternative reaction, we would expect the cross-section to increase by a factor of 300. In addition, the mass channel is less fragmented, i.e. only three open channels for A=141, and therefore, mass selectivity may well be sufficient for gamma-ray studies. As a result, we should be able to significantly enhance our knowledge of this nucleus beyond the few excited states we have already identified. The knowledge to be extracted would be a mapping of the low-lying single-particle states and a more detailed knowledge of the response of the nucleons to increased angular momentum. The latter may well help to determine the role of pairing in these loosely bound systems.

As another example, one is referred to the contribution by F. Kondev which discusses the use of proton-rich radioactive beams to study drip-line nuclei in the Pt-Hg region around $A = 170$.

Experimental Equipment

For high-spin studies, the use of radioactive ions will clearly enhance our knowledge of nuclei lying along the proton drip-line. The techniques we use are ones which are in use today, i.e. a highly efficient gamma-ray spectrometer coupled to ancillary detectors which indentify the particular nuclide produced. While these techniques are quite sensitive, they also result in lost efficiency. Both increases in detection efficiency of gamma-rays and particles will also enhance our abilities to perform these studies.