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Beta-Delayed Two-Proton Emission as a Nuclear Probe

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A brief history of beta-delayed two-proton emission is given. Speculations about future experiments which would enhance our knowledge about both nuclear spectroscopy and this relatively unique decay mode are presented.

Introduction

Beta-delayed particle emission has made the study of light proton rich nuclei much easier. In fact, as experiments have proceeded further from beta stability, detection of these exotic decay modes has become the probe of choice. Studies utilizing beta-delayed alpha and proton emission have become routine. Since a recent review¹ of all proton rich light nuclei covers the advantages of using delayed particle emission in eliciting the relevant physics, we will not attempt to give these reasons here. Instead, we will concentrate on how the discovery of a new isotope via its beta-delayed proton decay branch led to the discovery of a newly predicted^{2,3} decay mode, beta-delayed two-proton emission, on the mechanisms available for this decay mode, and on what new measurements might bring to light.

Extensive studies of nuclei via their strong beta-delayed proton decay branch were first made in the $A = 4n+1$, $T_z = -3/2$ series. These nuclei have been characterized in this manner from ^9C to ^{61}Ge ^{1,4}. Attempts to study the $A = 4n$, $T_z = -2$ series of strong beta-delayed proton emitters were thwarted until mass separated samples were available because of the simultaneous and copious production of the $A = 4n+1$, $T_z = -3/2$ nuclei. ^{32}Ar ⁵, ^{20}Mg , ^{24}Si , and ^{36}Ca ⁶ were all studied in this manner. Mass surface systematics suggested, however, that the proton energy which would be detected following decay from the analog state in the $T_z = -1$ daughters of the $A = 4n+2$, $T_z = -2$ nuclei would be generally higher than all proton energies arising from nuclei produced in competing reactions. Thus ^{22}Al became the first member of this series to be discovered by its beta-delayed proton decay⁷. This large βp energy in ^{22}Al also provided the unique possibility that *two* protons could be emitted following beta decay to the isobaric analog state. Figure 1 shows the result of a 110 MeV $^3\text{He} + \text{Mg}$ bombardment^{8,9}. This spectrum from the decay of ^{22}Al represents the discovery of beta-delayed two-proton

Figure 1. Proton-proton coincidence spectra obtained with a narrow angle detector system following the decay of ^{22}Al . See text and ref. 9. a) Two-proton summed energy spectrum. Groups x and g correspond to transitions involving the ^{20}Ne first excited state and ground state, respectively. b) Individual proton energy spectrum for protons forming group x in part a). Primed peaks probably correspond to the first emitted proton. c) Individual proton energy spectrum for protons forming group g in part a). In this case, g1 and g2' correspond to the first emitted protons.

two-proton emitter¹¹. Unfortunately, ^2He emission from the isobaric analog state in ^{26}Si to the ^{24}Mg ground state is spin/parity forbidden. Thus this decay must be sequential. The following section will discuss not only the potential for observing ^2He emission, but how beta-delayed two-proton emission can be used as a spectroscopic probe.

radioactivity. (The importance of the narrow angle designation in Fig. 1 will become obvious later.) The 'g' and 'x' designations refer to the ground and first excited state in the $2p$ daughter, ^{20}Ne . The individual proton spectra of these two sum peaks are also given in Fig. 1. It is in these single proton spectra in which the decay mechanism is most evident. There exist three distinct mechanism possibilities: sequential, correlated simultaneous, and uncorrelated simultaneous emission. These three mechanisms would manifest themselves in the individual spectra in very different ways. Sequential emission for this decay would be nearly isotropic with the second proton energy kinematically dependent upon the relative observation angle. Correlated simultaneous emission in the $1S_0$ state (^2He) would yield a strong angular dependence peaked at $\sim 40^\circ$ and essentially no yield observed beyond $\sim 65^\circ$ in addition to a continuum of single proton energies. Uncorrelated simultaneous emission would exhibit this same continuum of single proton energies, but would instead be essentially isotropic. Utilizing data obtained from a wide angle setup centered at 120° ⁹ and from an angular distribution measurement¹⁰, it was possible to ascertain that although a 15% admixture of ^2He emission cannot be excluded, the $\beta 2p$ decay of ^{22}Al proceeds predominantly by sequential emission. When statistics are sufficient, it is possible to determine which proton is emitted first by comparing data at different angles. This technique has been used with the proton groups shown for ^{22}Al in Fig. 1 to construct the decay scheme given in Fig. 2⁹. The beta-delayed single proton groups observed in ref.7 have also been incorporated into Fig. 2.

Subsequent experiments discovered that the next member of the $A = 4n+2$, $T_z = -2$ series, ^{26}P , is also a beta-delayed

New Studies

Once the initial characterization of beta-delayed two-proton emission was complete, the uniqueness of the decay mode could be exploited to search for heretofore experimentally inaccessible nuclei. The $\beta 2p$ spectrum arising from the 135 MeV $^3\text{He} + ^{40}\text{Ca}$ reaction shown in Fig. 3 represents the discovery of the first $T_z = -5/2$ nucleus, ^{35}Ca ¹², and the first time that beta-delayed two-proton decay had been used to discover a new nuclide. The evidence supporting the assignment of this $\beta 2p$ activity to ^{35}Ca has been summarized elsewhere ¹².

Subsequently, the existence of four $T_z = -5/2$ nuclei, ^{23}Si , ^{27}S , ^{31}Ar , and ^{35}Ca ¹³, was established in a fragmentation reaction study. Although the beta-delayed proton decay of ^{31}Ar has been determined ¹⁴, the predicted βp and $\beta 2p$ decay branches for the rest of these nuclei have yet to be reported.

Figure 2. Proposed partial decay scheme for ^{22}Al .

Figure 3. a) Beta-delayed two-proton sum spectrum of ^{35}Ca . Groups labeled by G and X are related to the two-proton transitions to the ground and first excited states in the daughter nucleus ^{33}Cl . Individual proton energy spectra are shown in b) and c) corresponding to the ^{35}Ca G and X 2p peaks, respectively.

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Figure 4. Proton rich portion of the chart of the nuclides from $Z = 10$ -32 depicting known and predicted beta-delayed and direct particle decaying nuclides.

Although only three examples of this decay mode have so far been demonstrated, many more could in principle exist. Figure 4 shows the light proton-rich section of the chart of the nuclides where those nuclei which could undergo $\beta_2 p$ decay are depicted. There are ~12 nuclei in the $Z = 10$ -32 region alone which would possibly exhibit this decay mode. The notation "strong" in Fig. 4. refers to cases where the isobaric analog state is open to the given decay mode. Searches for new beta-delayed two-proton emitters are, of course, hampered by the same problems which affect all studies as one proceeds further from beta stability: lower production rates and competing reactions which exhibit the same decay mode. For example, any compound nucleus reaction which would produce ^{27}S or ^{31}Ar would also produce ^{22}Al as background at some yield. Recoil spectrometers can in principle overcome this background problem, but

detection of the relevant decays can be difficult. Although medium energy fragmentation reactions have in general larger cross sections than similar compound nuclear reactions for such studies, the unique proton/neutron ratio of ^3He permits comparable cross section compound nuclear reactions. (Unfortunately, this is not true above $Z > 20$ due to the absence of stable $Z = N$ targets.) Recently, we attempted to observe the beta-delayed two-proton decays of ^{46}Mn and ^{50}Co in a $^{14}\text{N} + ^{40}\text{Ca}$ bombardment. Not only was the predicted cross section more than a factor of ten smaller than an "equivalent" ^3He induced reaction, the predicted $\beta 2p$ decay energies are < 2 MeV, requiring the observation of protons with energies less than 1 MeV.

Utilizing beta-delayed two-proton emission to search for new nuclei is only one interesting aspect of this nuclear probe. There are many unanswered questions about the decay itself. Three possible decay mechanisms have already been given. Since simultaneous uncorrelated two-proton emission appears least likely, we will only consider the other two mechanisms. Figure 5 gives the result of a Monte Carlo simulation⁹ of what would be observed for both sequential and ^2He emission using a detector system with $\sim 40^\circ$ relative angular range. Sequential emission would give a fixed energy first proton(s) but because the second proton is

Figure 5. Monte Carlo simulation of A) sequential and B) ^2He emission of two protons with $E_{\text{cm}} = 4.48$ MeV (a predicted ^{22}Al decay energy) as would be observed with a detector system capable of detecting the two protons with relative anangular range of $0-70^\circ$. a) Two-proton summed energy spectra. b) Individual proton energy spectra.

emitted from a moving source, the measured energy of this proton is dependent upon the relative emission angle. The width of the second proton peak and therefore the summed two-proton peak is dependent upon the solid angle subtended by the second detector. For instance, the summed peak width difference shown for ^{22}Al decay detected at narrow and wide angles in Ref. 9 is dependent upon the twofold difference in total solid angle subtended by the detector telescopes. The emission of ^2He would have a totally different signature. Such a decay would give a monoenergetic two-proton peak, independent of angle. The individual protons would comprise, however, part of an energy continuum centered at $E_{p1} = E_{p2}$. The relative angle of the two observed protons would peak at $\sim 40^\circ$; essentially no yield would be observed beyond 70° . Although evidence for this decay mechanism has not been found, it remains a very interesting possibility that deserves more experimental attention. Unfortunately, most of the remaining undiscovered $\beta 2p$ emitters will necessarily have higher proton numbers, where the Coulomb

Figure 6. Typical detector setup used with the LISE spectrometer for identifying proton rich nuclei and subsequently observing a beta-delayed proton event. See ref. 14 for additional details.

barrier for ^2He emission might favor sequential decay. Another facet of beta-delayed two-proton emission that has to date remained unexplored involves the

observation of low-energy single protons (100-1000 keV). This stems from a lack of suitable detectors, which in some cases (e.g., ^{50}Co) may have prevented the observation of the $\beta 2p$ decay branch. Since all known $\beta 2p$ groups have been assigned to decays from the isobaric analog state, detection of low energy protons might also permit the observation of $\beta 2p$ groups associated with strongly populated Gamow-Teller beta decays. Thus, the development of suitable low-energy proton detectors would significantly further our knowledge of beta-delayed two-proton emission.

Experiments designed to study the $\beta 2p$ decay mechanism and to observe new nuclei exhibiting $\beta 2p$ emission will be difficult. To fully appreciate the magnitude of the experimental difficulties which might be encountered, one can consider two examples.

Figure 6 depicts a typical detector setup

used with the LISE recoil spectrometer¹⁵ to identify separated reaction products. To study the subsequent radioactive decay of the collected sample (one atom at a time), the identification electronics is rapidly switched to utilize the silicon counters as proton detectors. If one wished to detect and properly identify two protons from the decay of an implanted atom, one would be faced with an extremely difficult proposition. In a recent experiment which observed the βp decay of ^{31}Ar ¹⁴, it was suggested that some of the events were potential $\beta 2p$ counts. Unfortunately, without proper identification of both protons, these assignments may remain inconclusive.

All initial beta-delayed two-proton studies were conducted utilizing the helium-jet technique. The short half-lives which are encountered near the proton drip line, however, soon

Figure 7. Schematic diagram of the fast rotating wheel setup for the study of short-lived radioactivities.

renders the 25 ms helium-jet transit time as a severe liability. Faster collection techniques must be used. One example of such a technique is the fast rotating wheel shown schematically in Fig. 7. This wheel is capable of studying nuclides down to $<100 \mu\text{s}$ half-life range. However, in order to obtain this short lifetime capability, the detectors must be operated very near the primary beam. This intense radiation field

forces the acquisition of data only during the beam-off phase of a pulsed accelerator beam. These experimental difficulties and low production cross sections can often be overcome because it is possible to observe this decay mode in a very high background: $1:10^5$ protons or $1:10^9$ betas. Finally, beta-delayed two-proton decay can provide unique insights into the general mechanisms in which nuclei in excited states lose their energy.

Summary

Beta-delayed two-proton emission is an interesting decay mode about which much more is to be learned. A more complete review of the current state of this decay mode may be found elsewhere ¹⁶. Many experiments remain to be performed which should give exciting new insights into the use of beta-delayed two-proton emission as a nuclear probe.

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