Studies of light nuclei beyond the particle driplines: the two-proton emitter $^{12}\text{O}$

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Abstract
The decay dynamics of the ground state two proton emitter $^{12}\text{O}$, which lies beyond the proton dripline, were investigated following the population of $^{12}\text{O}$ via single-neutron stripping of an $^{13}\text{O}$ projectile. The decay products, two protons and $^{10}\text{C}$, were detected in coincidence and correlations among these particles were studied. No evidence was seen for $^4\text{He}$ emission in the decay. This appears consistent with direct breakup or possibly sequential decay through $^{11}\text{N}$.

1. Introduction
While much of the interest in exotic nuclei in recent years has focused on particle-stable systems near the driplines, there are many interesting questions regarding particle-unstable nuclear systems beyond both the proton- and neutron-rich limits of stability. Most of our current knowledge of these nuclei follows from reactions in which they are produced as unobserved reaction products. Although these techniques can provide important information on quantities like the nuclear mass, some properties such as decay modes cannot be investigated in this fashion. At the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University, we are developing techniques to study these nuclei more directly through the observation of their decay products. To date, we have carried out studies of a range of particle-unstable nuclei from $^{10}\text{Li}$ on the neutron-rich side [1] to the ground state two proton emitter $^{12}\text{O}$ on the proton rich side. In this paper, we focus on our recent study of $^{12}\text{O}$ which incorpo-

rates the use of radioactive secondary beams with a kinematically complete decay study.

Over thirty years ago Goldanskii predicted the existence of ground state two proton (2p) emission in proton-unbound even-Z nuclei where the pairing energy between the last two protons causes the one proton decay channel to be energetically forbidden [2]. In contrast to decay by one particle emission, two proton decay can theoretically proceed through several competing mechanisms including direct three-body breakup and sequential binary decay channels. The additional information inherent in a three body decay may provide an important tool to study the structure of proton-rich nuclei at the limits of stability. Current mass measurements indicate that $^6\text{Be}$, $^{12}\text{O}$, and $^{16}\text{Ne}$ are ground-state 2p emitters [3,4]. Only the decay of the lightest case $^6\text{Be}$ has been studied experimentally [5,6]; investigation of the heavier systems has been hampered because they are far from stability.

The two proton decay $Q$-value of $^{12}\text{O}$ $Q_{2p}$ is 1.79(04) MeV and the width of the ground state has been estimated to be 400(250) keV [3,4]. The lowest lying known state in the one proton (1p) decay daughter $^{11}\text{N}$ has a decay $Q$-value $Q_{1p} = 2.2(1)$ MeV and a width of 740(100) keV which is consistent with a $p$-wave resonance ($J^p = \frac{1}{2}^-$) [3,7]. The ground state may actually be a broader $s$-wave state ($J^p = \frac{1}{2}^+$) since the analog $^{11}\text{Be}$ ground state is determined by a neutron in an intruder s-shell [8]. Branching ratio estimates for the 2p decay of $^{12}\text{O}$ have suggested...
that the decay might be dominated by the emission of the protons in a correlated singlet state (i.e. $^4\text{He}$ emission), accounting for up to 90% of the decay branch [9–11]. However, similar estimates for $^6\text{Be}$ also predict a very large $^4\text{He}$ branching ratio, but Bochkarev et al. [6] found that the two proton decay of $^6\text{Be}$ is not dominated by $^4\text{He}$ decay. Rather, they find evidence for a complex mixture of decay modes including a small diproton contribution ($\sim 20\%$) which they attribute to the structure of the $^6\text{Be}$ wavefunction and/or to Coulomb final state interactions. The present experiment was designed to produce $^{12}\text{O}$ as a projectile-like fragment and then detect the three decay products in coincidence.

2. Experimental technique

The experiment was performed at the NSCL using a radioactive secondary $^{13}\text{O}$ beam to populate the $^{12}\text{O}$ parent nucleus via the $^9\text{Be}(^{13}\text{O},^{12}\text{O})$ single neutron stripping reaction. The $^{13}\text{O}$ beam intensity averaged 2400 cps with an energy of 33.4 MeV/A incident on the $^9\text{Be}$ target. The purity of the $^{13}\text{O}$ beam was 98% with a 2% $^{12}\text{N}$ contamination which was identified particle-by-particle using time-of-flight. Details on the production of the radioactive $^{13}\text{O}$ beam are given elsewhere [12].

Heavy reaction products were detected in a $\Delta E-E$ silicon telescope located 84 cm down-stream of the target, directly at 0°. The $\Delta E$ detector consisted of a 5 cm by 5 cm double-sided strip detector with 16 vertical strips on the front and 16 horizontal strips on the back. The detector thickness was 304 $\mu$m and the strips yielded x–y position information in addition to energy-loss. The $E$ detector consisted of a 6.5 cm diameter, 3 mm thick Si(Li) detector with four pie-shaped segments. Isotope identification for $Z = 6$ fragments was achieved using the $\Delta E-E$ information and the total fragment energy was determined from the sum of the two detector signals. The detectors were calibrated using $^{10}\text{C}$ beams produced at several energies using the A1200 fragment separator. Protons were detected in the Washington University MINIWALL detector array [13] positioned approximately 60 cm downstream of the target. This detector array was composed of 112 CsI detectors arranged in five rings around the beam axis covering laboratory angles between 3° and 12°. Proton signals were distinguished from other light particles using pulse shape techniques [13]. These detectors were energy calibrated using elastically-scattered protons at several energies.

Data were taken with and without the target and the target-out background was found to be negligible. The $2p + ^{10}\text{C}$ events were identified offline and random coincidences, on the order of 5%, were subtracted from the data. In addition, we subtracted a 15% contamination from the data due to $2p + ^{14}\text{C}$ events arising from imperfect isotope separation in the $\Delta E-E$ detectors.

3. Results and discussion

Fig. 1 shows the relative energy spectrum for the $2p + ^{10}\text{C}$ coincidence data. The spectrum is dominated by a peak with energy corresponding to the decay $Q$-value of the $^{12}\text{O}$ ground state. Both the decay $Q$-value and the width are consistent with previous measurements when the detector resolution is taken into account. We estimate the single neutron stripping cross section in the $^9\text{Be}(^{13}\text{O},^{12}\text{O})$ reaction to be on the order of 1 mb based upon the observed yield. The events in the spectrum above the main peak likely correspond to excited states of $^{12}\text{O}$.

Fig. 2 shows a three-body Dalitz plot for the $2p + ^{10}\text{C}$ events with relative energy corresponding to the $^{12}\text{O}$ ground state. The ellipse in the figure demarcates the region of momentum conservation. A Dalitz plot is convenient for looking at correlations in three-body decays because a pure phase space decay leads to an equal distribution of data points within the momentum-conserving ellipse [14]. In our case, we see a deficit of events near the sides of the ellipse corresponding to events with a small energy difference between one of the protons and the $^{10}\text{C}$ fragment. Qualitatively, this effect might be expected due to the Coulomb repulsion between the protons and the heavy fragment.

The top of Fig. 3 shows the opening angle distribution between the two protons (evaluated in the center-of-mass)
arising from the decay of the $^{12}$O ground state. The dotted histogram shows a model calculation for decay by $^3$He emission which incorporates the detector acceptances and resolution. Details of this model are given elsewhere [12]. The data are approximately isotropic and show no evidence for strong angular correlations, and differ quite substantially from the $^3$He emission model. We have set an upper limit of 7% (95% CL) on the $^3$He branching ratio based on these results. The bottom of Fig. 3 shows the energy difference spectrum of the two protons (evaluated in the center-of-mass) for the same events. The data show a broad peak centered at approximately zero energy difference, indicating that near equal energy proton emission is preferred. For comparison, the dashed histogram shows the expected distribution for a pure phase-space decay and sequential one proton decay, respectively.

One simple hypothesis which can account for our results is if the $^{11}$N ground state sits near $Q_{1p} \sim 0.5Q_{2p} \sim 0.9$ MeV. In this case, $^{12}$O would decay by sequential one proton emission through $^{11}$N, leading to a near isotropic opening angle distribution for the protons and an energy difference spectrum similar to the measured spectrum. The solid histograms in Fig. 3 correspond to the calculated spectra for sequential one proton decay through $^{11}$N with a ground state at $Q_{1p} = 0.9$ MeV and a 1.5 MeV width. The calculation, which included Coulomb penetration factors in the emission of both protons as well as detector acceptances and resolution [12], reproduces the data relatively well. This hypothesis also explains the small $^3$He branch since this mechanism is not expected in sequential one proton decay. In this scenario, $^{12}$O would no longer be classified as a ground state two proton emitter. However, the proposed decay energy for $^{11}$N is well below current predictions [15]. To address this possibility, we plan to investigate the level structure of $^{11}$N in an upcoming experiment.

An even more interesting possibility arises if the $^{11}$N ground state decay energy is above the $^{12}$O two proton decay energy ($Q_{1p} > Q_{2p}$) as expected. In this case, the near equal-energy proton emission coupled with the small $^3$He branching ratio would seem to indicate that the $^{12}$O decay proceeds through a direct breakup process. A similar conclusion was reached by Bochkarev et al. [6] in their study of $^6$Be. They termed this type of three-body decay, which is not dominated by long-lived sequential binary channels, “democratic”. In the case of $^6$Be, the measured energy and angular correlations of the decay products have been understood in terms of a direct decay process using a three-body cluster model [6,16]. They find that the correlations in the decay products may be directly related to correlations present in the parent wavefunction before decay. We are presently exploring a similar cluster model for the $^{12}$O decay.

4. Summary and outlook

To summarize, we are developing experiments which probe nuclei just beyond the particle driplines on both the proton- and neutron-rich limits of stability with the intent to investigate the structure and decay modes in these nuclear systems. Our recent study of the two proton decay of $^{12}$O emphasizes the role of radioactive nuclear beams and shows the high quality of data which can be obtained with even modest secondary beam rates. We have measured the energy and angular correlations in the $2p + ^{10}$C final state from the decay of ground state $^{12}$O and found no evidence for $^3$He emission within our limits of sensitivity. Final interpretation of these data awaits an upcoming investigation of the level structure of $^{11}$N as well as further theoretical study of the $^{12}$O system.

References


[13] The detectors and signal processing techniques were very similar to those used in Stracener et al., Nucl. Instr. and Meth. A 294 (1990) 485, except the fast plastic scintillator layer was not used.

