Two-Proton Emission from the Ground State of ^{12}O

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The three-body decay $^{12}O \rightarrow 2p + {}^{10}C$ was studied following production via single-neutron stripping from a radioactive ^{13}O projectile. This is the first observation of two-proton emission from an unbound ground state where the one-proton emission channel is energetically closed beyond the lightest case of ^6Be. No evidence for ^2He emission is seen, despite predictions for a large diproton branching ratio. An upper limit of 7% (95% C.L.) is established for this decay branch. The implications of the small diproton branching ratio observed here and seen previously in ^6Be are discussed.

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Over 30 years ago Goldanskii predicted the existence of ground-state two-proton ($2p$) radioactivity in particle unbound (proton-rich) even-Z nuclei where the pairing energy between the last two protons causes the one-proton decay channel to be energetically forbidden [1]. 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. Branching ratio estimates made using the R-matrix approximation have suggested that diproton (^2He) emission, corresponding to decay via protons correlated in a ^1S state, might dominate [2–4]. Current mass measurements indicate that ^6Be, ^{12}O, and ^{16}Ne are ground-state $2p$ emitters [5,6], although in all of these cases the width of the ground states are known to be relatively large and consequently the decay times are very fast ($\leq 10^{-20}$ sec). Only the decay of the lightest case ^6Be has been studied experimentally [7,8]. Higher Z candidates with much longer lifetimes due to the larger Coulomb barrier have been predicted and searched for [4,9–13]. Understanding the two-proton decay mechanism is important because it provides a window into the structure of very proton-rich nuclei. As an example, the ^2He emission probability depends directly on the diproton spectroscopic factor of the parent system [3,4]. More generally, it is important to understand the specific features of multibody nuclear decay modes since these channels become increasingly important for nuclei far from stability.

We report on a kinematically complete study of the $^{12}O \rightarrow 2p + {}^{10}C$ decay. The decay Q value Q_{2p} is 1.79(04) MeV, and the width of the ground state has been estimated to be 400(250) keV [5,6]. The lowest known state in the one-proton ($1p$) decay daughter ^{11}N has a $1p$ decay Q value $Q_{1p} = 2.2(1)$ MeV and a width of 740(100) keV which is consistent with a p-wave resonance ($J^\pi = \frac{1}{2}^-$) [5,14]. The actual ground state may be a broader s-wave state ($J^\pi = \frac{1}{2}^+$) since the analog ^{11}Be ground state is determined by an intruder s-shell level [15]. Audi and Wapstra predict the decay energy of the ^{11}N ground state to be $Q_{1p} = 1.97(18)$ MeV [6], approximately 200 keV higher than the $2p$ decay energy of ^{12}O. Therefore, sequential one-proton decay through ^{11}N is expected to be suppressed, occurring only through the tail of the ground state. Kekelis *et al.* estimated the diproton branching ratio for ^{12}O to be 30%–90%, assuming a spectroscopic factor for ^2He emission of unity [3]. A more realistic calculation of the spectroscopic factor is 0.6, following the method of Ref. [4], which still yields a large branching ratio. Similar estimates for ^6Be predict a much larger ^2He branching ratio, however, Bochkarev *et al.* [8] found that the two-proton decay of ^6Be is not dominated by ^2He decay. Rather, they find evidence for a complex mixture of decay modes including a small diproton contribution (~20%) which they attribute to the structure of the ^6Be wave function and/or the result of Coulomb final state interactions.

The present experiment was performed at the National Superconducting Cyclotron Laboratory using an exotic ^{13}O beam and the $^9Be(^{13}O, {}^{12}O)$ single-neutron stripping reaction to populate the ^{12}O parent nucleus. The radioactive ^{13}O beam was produced in the fragmentation of 80 MeV/nucleon ^{16}O on a 1000 mg/cm^2 Be production target. The secondary beam was separated using a 100 mg/cm^2 Al achromatic wedge in the A1200 fragment separator [16] and further purified with the Reaction Product Mass Separator (RPMS) [17]. Behind the RPMS, the

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^{13}O beam was incident on a 47 mg/cm^2 Be secondary reaction target. A thin plastic scintillator behind the RPMS was used to measure the secondary beam time of flight (TOF) relative to the cyclotron RF signal. The purity of the ^{13}O beam was determined to be 98%, with a 2% ^{12}N contamination, using a silicon ΔE detector in conjunction with the TOF. During the coincidence runs, this silicon detector was removed and the beam identification was monitored event by event using the TOF signal; the beam contamination was well separated in time from the ^{13}O. The final ^{13}O beam intensity averaged 2400 cps and the energy of the beam incident on the secondary target was 33.4 MeV/nucleon. The beam spot size was approximately 1 cm (FWHM).

Heavy reaction products were detected in a ΔE-E silicon telescope placed 84 cm downstream of the target, directly at 0°. The ΔE 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 μm, 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 was achieved using the ΔE-E information, and the total fragment energy was determined from the sum of the two detector signals. The detectors were calibrated using ^{10}C beams produced at several energies using the A1200 fragment separator. Protons were detected in the Washington University Miniwall detector array [18] positioned approximately 60 cm downstream of the target. This detector array was composed of 112 CsI detectors arranged in 5 rings around the beam axis covering laboratory angles between 3° and 12°. Each ring contained between 16 and 24 detectors so that proton angle was determined in addition to the energy. Proton signals were distinguished from other light particles using pulse shape techniques [18]. These detectors were energy calibrated using elastically scattered proton beams at several energies. Data were taken with and without the target, and the target-out background was found to be negligible. The $2p$ + ^{10}C events were identified off-line, and the energies and angles of the three particles were determined. Random coincidences, on the order of 5%, were subtracted from the data.

Figure 1 shows the decay energy spectrum for the $2p$ + ^{10}C coincidence data. The spectrum is dominated by a peak with energy corresponding to the decay Q value of the ^{12}O ground state. A Gaussian fit to this peak gives an energy of 1.77(02) MeV and a width of 784(45) keV. We estimate our experimental resolution to be 530(200) keV, based upon Monte Carlo simulations of the experimental setup. Subtracting this resolution yields an intrinsic width for the state of 578(205) keV. Both the decay Q value and the width are consistent with previous measurements. Some counts are also seen in the spectrum at higher energies which likely correspond to excited states of ^{12}O [19]. In principle the $2p$ + ^{10}C coincidence events could arise from projectile breakup of ^{13}O without passing through an intermediate ^{12}O state. However, the observed energy correlation in Fig. 1 clearly indicates that the ^{12}O ground-state resonance is formed in the collision process. Figure 2 shows the energy difference spectrum of the two protons for events where the total decay energy corresponds to the ^{12}O ground-state peak. The energy difference is evaluated in the three-particle center of mass (c.m.), and the spectrum shows a broad peak centered at approximately zero energy difference, consistent with predominantly equal energy protons emitted in the decay. Figure 3 shows the opening angle distribution between the two protons evaluated in the c.m. for decays arising from the ^{12}O ground state. The data are approximately isotropic and show no evidence for strong angular correlations.

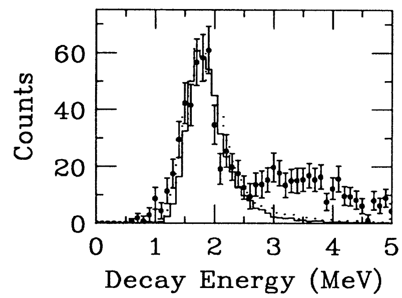

FIG. 1. Decay energy of the $2p$ + ^{10}C coincidence events. The dotted histogram shows the results of a calculation based upon ^{2}He emission, and the solid histogram shows the results based upon sequential emission through the tail of a broad ^{11}N state.

We can model the three-body decay as two successive binary decays within the R-matrix approximation with two limiting cases: decay through ^{2}He emission and sequential $1p$ decay through ^{11}N. In both cases, we can describe the line shape in terms of the total decay energy E and the relative energy of the second decay U as

$$N(E,U) \sim \frac{\Gamma_1(E,U)}{(E - Q_{2p})^2 + \frac{1}{4}\Gamma_{\rm tot}^2(E)}, \tag{1}$$

where Q_{2p} is the $2p$ decay Q value and $\Gamma_{\rm tot}(E)$ is the total width of the parent state. The partial width is

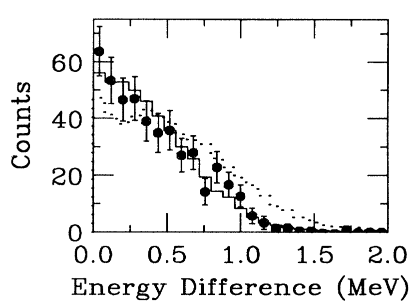

FIG. 2. Energy difference spectrum evaluated in the three-particle center of mass for protons arising from the decay of the ^{12}O ground state. The dotted histogram shows the results of a calculation based upon ^{2}He emission, and the solid histogram shows the results based upon sequential emission through the tail of a broad ^{11}N state.

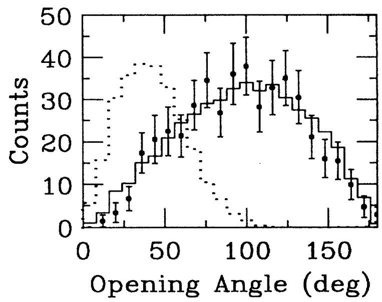

FIG. 3. Opening angle spectrum evaluated in the three-particle center of mass for protons arising from the decay of the ^{12}O ground state. The dotted histogram shows the results of a calculation based upon ^{2}He emission, and the solid histogram shows the results based upon sequential emission through the tail of a broad ^{11}N state. The ^{2}He calculation has been scaled down by a factor of $\frac{1}{2}$.

given by $\Gamma_1(E,U) = 2\,\theta_1^2\,\gamma_1^2\,P_\ell(E-U)\rho(U)$, where θ_1^2 and γ_1^2 are the spectroscopic factor and reduced width, respectively, associated with the emission of the first particle (either ^{2}He or p), $P_\ell(E-U)$ is the penetrability for angular momentum ℓ, and $\rho(U)$ is the density of states in the intermediate channel [20–22]. For the case of ^{2}He emission, we used a parametrization from Ref. [23] of the final state interaction theory expression for $\rho(U) \propto \sin^2\delta(U)/(C^2U)$, where $\delta(U)$ is the ^{1}S pp phase shift, $C^2 = \eta/(e^{2\pi\eta}-1)$, and η is the Sommerfeld parameter [24]. For sequential emission through ^{11}N we used the standard R-matrix expression [20]

$$\rho(U) = \frac{1}{2\pi}\frac{\Gamma_2(U)}{(U-Q_{1p})^2 + \frac{1}{4}\Gamma_2^2(U)}, \qquad (2)$$

where Q_{1p} is the Q value for $1p$ decay of the ^{11}N ground state and $\Gamma_2(U)$ is the width of this state. Implicit in $\Gamma_2(U)$ is a spectroscopic factor, reduced width, and penetrability associated with the emission of the second proton. These line shapes were incorporated into a Monte Carlo simulation which included the geometric acceptance as well as the energy and angular resolutions of the detectors. The total width was defined as $\Gamma_{\rm tot}(E) = \int \Gamma_1(E,U)\,dU$, and the constants in the partial width were determined by the requirement that $\Gamma_{\rm tot}(Q_{2p}) = 580$ keV, the measured ground-state width. The dotted histograms in Figs. 1–3 show the results of the ^{2}He emission calculation ($\ell = 0$ assumed), normalized to the decay energy data. The calculated proton opening angle spectrum is in clear disagreement with the data which show no small angle enhancement. The energy difference spectrum is also significantly broader than the data. We extract an upper limit of 7% (95% C.L.) for the ^{2}He branching ratio based upon the calculated distribution and the deviation of the opening angle data from isotropic emission. The solid histograms show the result of a sequential decay calculation through the tail of a ^{11}N state. For this calculation we used $Q_{1p} = 1.9$ MeV and took $\Gamma_2(Q_{1p}) = 1.5$ MeV [3] to reflect the broader expected width of the ^{11}N ground state relative to the known state at $Q_{1p} = 2.2(1)$ MeV. We also assumed $\ell = 0$ emission for both protons. Although this decay channel is strongly suppressed due to the available energy, requiring an unrealistically large reduced width for the ^{12}O ground state ($\theta_1^2\gamma_1^2 \sim 45$ MeV) to reproduce the measured total width, the calculation does provide a good fit to the energy difference and opening angle spectra (the proton decays were assumed isotropic) as well as to the decay energy spectrum.

The small ^{2}He branching ratio could be explained if the ^{11}N ground state were located at $Q_{1p} \approx \frac{1}{2}Q_{2p} \approx 0.9$ MeV, in which case ^{12}O would decay sequentially by one-proton emission and it would no longer fulfill the definition of a ground-state two-proton emitter. Under these conditions, one can obtain an equally good fit to the data as the solid histograms in Figs. 1–3 with quite reasonable values for the ^{12}O ground-state reduced width ($\theta_1^2\gamma_1^2 \sim 2$ MeV). However, this resonance energy is well below current predictions for the ^{11}N ground state [6,25]. Even in the absence of a low-lying ^{11}N ground state, it is likely that previous estimates of the ^{2}He branching ratio were too large. These estimates [2–4] did not take the specific properties of the broad ^{2}He state into account. Instead, they used the R-matrix formalism suitable for the emission of a very long-lived particle which is obtained by replacing the density of states $\rho(U)$ in the expression for the partial width by a delta function $\delta(U-\epsilon)$, where ϵ is the assumed energy of the ^{2}He state. In this case, after integration of the partial width $\Gamma_1(E,U)$ over the relative energy U and assuming the Wigner limit for γ_1^2 (1.6 MeV), $\theta_1^2 = 0.6$, and $\epsilon = 150$ keV, we obtain a total width of 225 keV corresponding to a branching ratio of ~40%. On the other hand, if we use the final state interaction expression for $\rho(U)$ and further normalize the density of states by $\int_0^\infty \rho(U)\,dU = \frac{1}{3}$ we obtain a total width of only 16 keV, well within our measured branching ratio limit. The factor of $\frac{1}{3}$ in the normalization of the density of states follows because the pp singlet state is a virtual state which corresponds to a scattering density of states of approximately $\frac{1}{3}$ [26–28]. A similar calculation for the ^{6}Be system, however, continues to overestimate the ^{2}He branching ratio compared with the results of Bochkarev *et al.* [8], unless a very small spectroscopic factor ($\theta^2 \sim 0.06$) is assumed. Furthermore, in this case the structure of the intermediate system ^{5}Li is well known so that sequential $1p$ decay through an energetically allowed ^{5}Li state can be discounted.

A third explanation for the small diproton branching ratio in both ^{6}Be and ^{12}O is that the R-matrix approximation, which assumes that the three-body decay can be described in terms of successive binary decays, is not valid for these $2p$ decay processes. This was the conclusion of Bochkarev *et al.* [8] in their study of the ^{6}Be because they saw little evidence for ^{2}He emission and because they argued that sequential one-proton emission through the tail of a broad intermediate state ($\Gamma \approx 1.5$ MeV for the ^{5}Li ground state [5]) is not distinguishable from three-body breakup because of the short lifetime of the intermediate state. They termed this type of three-body decay, which is not dominated by long-lived sequential binary decay, "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 [8,29]. A similar argument can be made for democratic decay in the ^{12}O system because of the small ^{2}He branch and the broad expected width of the ^{11}N ground state. We speculate that the relatively good agreement between the ^{12}O data and the sequential decay model through the tail of the ^{11}N ground state may result because this model approximates a direct three-body decay.

Finally, we can compare the $2p$ emission from ^{12}O with β-delayed $2p$ emission seen in a number of nuclei ranging from ^{22}Al to ^{39}Ti [30]. In all of the β-delayed cases, the sequential $1p$ decay channel is open, and consequently we expect the sequential decay mechanism to dominate. In fact, this is found to be true, and no evidence has been seen for ^{2}He emission in any of the β-delayed $2p$ emitters [30,31]. In contrast, the ground-state $2p$ emitters should be much more sensitive to ^{2}He emission because the sequential $1p$ channel is closed.

The small ^{2}He branch measured here and in ^{6}Be [8] suggests that this decay channel is much weaker than originally thought in both the β-delayed and ground-state $2p$ emitters. However, because of the very short lifetime of the ^{12}O and ^{6}Be ground states, it is not possible to entirely rule out the influence of the other reaction products on the $2p$ decay dynamics. Even so, the lifetime of the ^{12}O ground state is over a factor of 5 larger than the estimated ^{13}O neutron stripping time.

To summarize, we have used a single-neutron stripping reaction with a radioactive projectile to study the ground-state two-proton decay of ^{12}O. The decay is found to favor the emission of equal energy protons with an isotropic angular distribution. No evidence is seen for ^{2}He emission and an upper limit of 7% is set for this branching ratio. In the absence of a very low-lying ^{11}N ground state, the small ^{2}He branching ratio in ^{12}O suggests that the $2p$ decay proceeds through direct three-body breakup.

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