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The previously measured decay of the ground state of ^{12}O was reanalyzed based on new experimental and theoretical results for the ground state of ^{11}N. In the previous analysis no evidence for di-proton emission was found and the measured large decay width was inconsistent with sequential proton decay via the intermediate system of ^{11}N. The recent results on ^{11}N show evidence that the ground state of ^{11}N is at substantially lower energy allowing for a consistent explanation of the two-proton decay of ^{12}O in terms of sequential proton emission.

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The recent availability of radioactive beams has opened the possibility to study nuclei along the driplines increasing the feasibility to search for di-proton emitters of proton rich nuclei over a wide mass range [1,2]. For example, ^{12}O was predicted to have a substantial ground state di-proton branch [3] based on the adopted value for the ground state of ^{11}N at 100 keV above the one-proton threshold of ^{12}O. Thus the sequential proton decay branch through this intermediate state would be strongly suppressed favoring di-proton emission.

In a measurement of the decay of ^{12}O, no evidence for correlated two-proton emission was observed [1]. The strongly suppressed sequential decay through the tail of a broad ground state of ^{11}N is not consistent with the observed large decay width of ^{12}O [1,3]. However, the ground state of ^{11}N was only deduced from systematics [4] and had not been measured at the time. Recent calculations [5,6] and experiments [7,8] present evidence for a substantially lower value for the ground state of ^{11}N. In the present paper we reanalyze the results of the ^{12}O decay measurement [1] to test the consistency with these new results.

In this experiment ^{12}O was populated via the one neutron stripping reaction from a radioactive beam of ^{13}O. The lifetime of ^{12}O is extremely short ($\sim 10^{-21}$ s) decaying into ^{10}C by emitting two protons. The decay energy spectrum, relative energy of the two protons, as well as the opening angle between the two protons were determined in a kinematically-complete experiment detecting all decay products. Further details of the experiment can be found in reference [1]. A decay energy of 1.77(02) MeV and a decay width of 578(205) keV for the ground state of ^{12}O were extracted which are consistent with previously reported values of 1.79(04) MeV and 400(250) keV, respectively [3,9,10].

The 1.8 MeV decay energy of the ground state of ^{12}O would make it bound to one proton emission by 100 keV based on the previously estimated ^{11}N ground state. This ground state estimate was based upon a study of ^{11}N which observed a proton unbound state with a decay energy of 2.24(10) MeV which was interpreted as the $p_{1/2}$ first excited state. The ground state of ^{11}N was predicted to be an $s_{1/2}$ state similar to the level inversion observed in the mirror nucleus ^{11}Be [9,11]. Calculations using the Isobaric Multiplet Mass Equation (IMME) predicted the $s_{1/2}$ state to be unbound to proton decay by 1.9 MeV [4]. The width was predicted to be large due to the s-wave character of this state. Even though a 1.9 MeV decay energy ground state within ^{11}N is energetically closed to ^{12}O decay by 100 keV, the sequential decay could proceed through the tail of this state. In reference [1] results of simulations of this sequential decay were in good agreement with the data, however, in order to reproduce the decay width of ^{12}O an unrealistically large reduced width of 42 MeV for ^{12}O was necessary, in comparison to the calculated Wigner limit of 3.3 MeV. Details of the simulations can be found in reference [1]. The large reduced width is needed due to the strong suppression of low energy proton emission in the presence of the Coulomb barrier. A lower ^{11}N ground state energy reduces the barrier, thus the data could potentially be explained with reasonable values for the reduced width.

Recent calculations and experimental observations of ^{11}N indeed report a lower decay energy for the ground state. Sherr [12] questioned the accuracy of the isospin assignments of the states in ^{11}C and ^{11}B used in the original IMME calculations. He reanalyzed the available data and obtained a decay energy of 1.5(1) MeV. Similarly, potential model calculations for the ground state of ^{11}N [5,6] resulted in a decay energy of 1.6 MeV. A recent experiment [7] using the reaction p(^{10}C,^{10}C$'$)p$'$ measured a decay energy of 1.30 ± 0.04 MeV and a width of 990^{+100}_{-200} keV for the ground state of ^{11}N. A second experiment used the one neutron stripping reaction ^{9}Be(^{12}N,^{11}N) and found evidence for a decay energy of 1.45 MeV and a width of 2.4 MeV for the ground state of ^{11}N [8]. Another recent experimental study of the ^{11}N [13] system did not observe evidence for the $2s_{1/2}$ ground state in the reaction ^{12}C(^{14}N,^{15}C)^{11}N. However, in this reaction any $2s_{1/2}$ resonance is strongly hindered and difficult to observe in the presence of background and the strongly populated p states.

The decay energy and width of ^{11}N determine the total decay width of ^{12}O which is directly related to the reduced width. Figure 1 shows the total ^{12}O decay width as a function of the reduced width for several values of the ^{11}N decay energy at a fixed width of 2 MeV assuming a sequential decay. The lower limit of the measured ^{12}O decay width [3] (horizontal line) and the Wigner limit (vertical line) provide an upper limit for the ^{11}N decay energy. The shaded area corresponds to the region which satisfies both conditions, a total width consistent with the measured value and a reduced width which is smaller then the single particle width (Wigner Limit). Lines of different ^{11}N decay energies which pass through this region represent the possible decay energies for the ground state of ^{11}N. Thus the maximum decay energy for ^{11}N still consistent with these constraints is ~ 1.45 MeV for a ^{11}N width of 2 MeV. This value depends only weakly on the ^{11}N width and varies from 1.3 MeV to 1.5 MeV for a range of widths between 500 keV and 3 MeV.

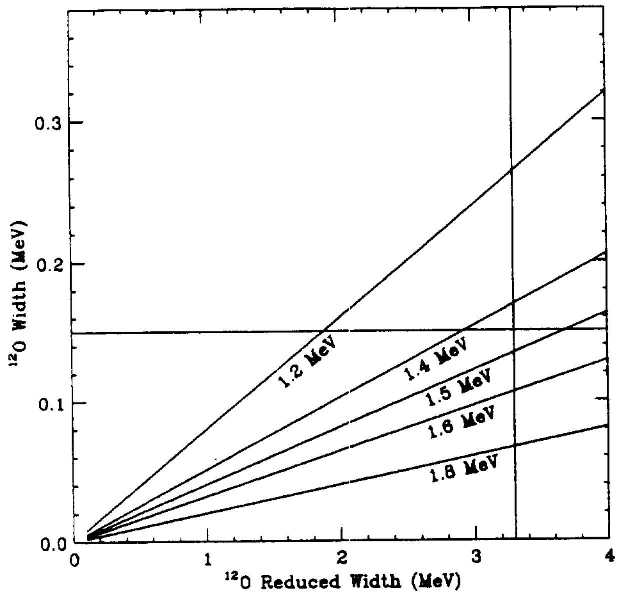

FIG. 1. Total ^{12}O decay width as a function of the reduced width assuming sequential emission via ^{11}N. The solid horizontal line represents the lower limit on the experimental total width of the ground state of ^{12}O. The vertical line at 3.3 MeV is the Wigner limit on the reduced width of the ground state of ^{12}O. The shaded upper-left region satisfies both requirements. By varying the decay energy of the ground state of ^{11}N, using a width of 2.0 MeV, the solid slanted lines were obtained. Lines which pass through the valid region represent the possible decay energies for the ground state of ^{11}N.

The Wigner limit as the upper limit for the reduced width assumes a pure $s^2_{1/2}$ configuration for the last two protons of ^{12}O. The ground state of the mirror ^{12}Be is predominantly $s^2_{1/2}$ [14,15] and a large fraction of $s^2_{1/2}$ can therefore be expected also for ^{12}O. If this fraction is smaller than 100% the upper limit of the reduced width would be more stringent. For example assuming 80% $s^2_{1/2}$ would reduce the upper limit for the ^{11}N decay energy to ~ 1.35 MeV.

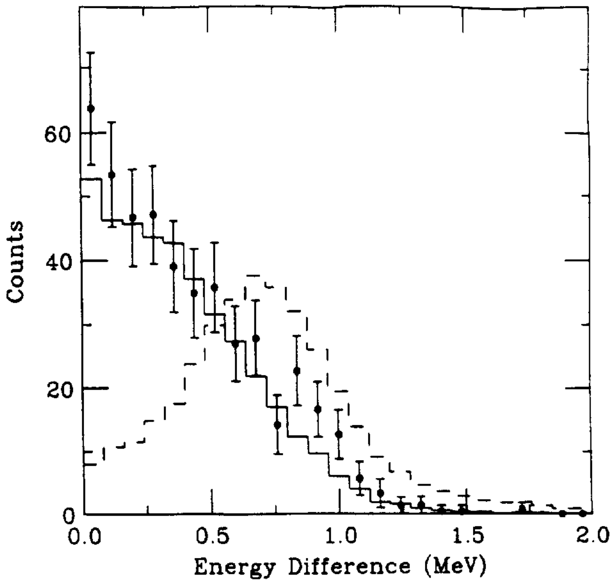

FIG. 2. Proton energy difference for the decay of ^{12}O. The solid histogram was obtained from a simulation using a decay energy of 1.9 MeV and a width of 1.5 MeV for the ground state of ^{11}N. The dashed histogram was obtained by using a decay energy of 700 keV and a width of 1.5 MeV for the ground state of ^{11}N.

A lower limit on the decay energy of ^{11}N can be obtained from the relative energy between the two protons measured in reference [1]. Since penetrability considerations favor the emission of protons with equal energy, if the decay energy of ^{11}N is larger than 900 keV (half of the ^{12}O decay energy), the decay proceeds through the tail of the state in ^{11}N to equalize the decay energy of each proton. For lower energies, the relative energy corresponds to the difference between the first ($^{12}O \rightarrow {}^{11}N + p_1$) and second decay ($^{11}N \rightarrow {}^{10}C + p_2$). Figure 2 shows the measured proton relative energy spectrum together with simulations for ^{11}N decay energies of 1.9 MeV (solid) and 700 keV (dashed). While the first simulation peaks at a relative energy of zero, the second simulation peaks at approximately $E_{p_1} - E_{p_2} = 1.1MeV - 0.7MeV = 0.4MeV$. Thus a lower limit for the decay energy of ^{11}N can be extracted at ~ 700 keV.

As the recent experimental and theoretical results for the ground state of ^{11}N are in agreement with the limits considered above, Monte Carlo simulations similar to the calculations shown in reference [1] were performed using the two experimental values for the decay energy and width of the ground state of ^{11}N [3,8]. These simulations were performed assuming an s-wave proton in the ^{12}O ground state based on the structure of the mirror nucleus ^{12}Be [14,15]. Figure 3 shows the decay energy of ^{12}O (top), the relative proton energy (center) and the opening angle (bottom) for a ^{11}N decay energy of 1.45 MeV (Γ = 2.4 MeV) [8] and 1.30 MeV (Γ = 990 keV) [7] on the left and right sides, respectively. The simulations were fitted to the data using the same normalization factors. They are in good agreement with all experimental observables confirming that the ^{12}O data is compatible with sequential proton emission. The data contained in the tail of the decay energy spectrum is due to the decay of higher excited states and was not included in the comparison of the relative energies and opening angles.

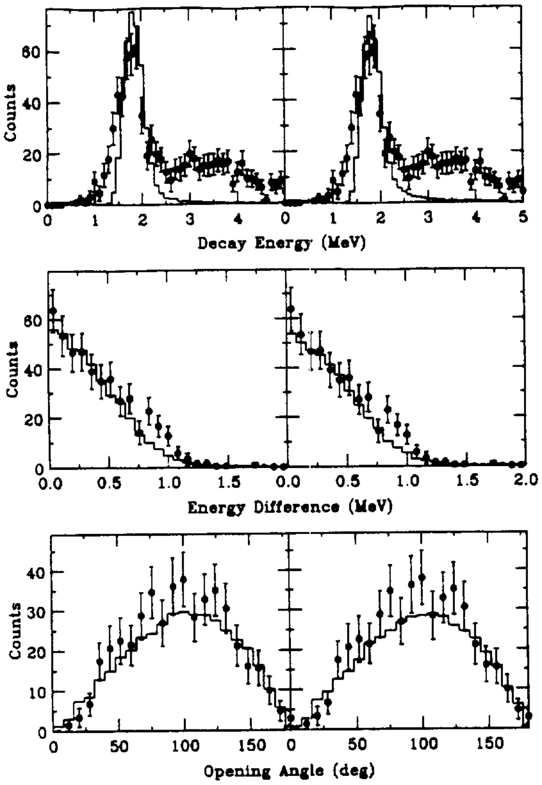

FIG. 3. Comparison of simulation to data obtained for ^{12}O for the experimental observables decay energy (top), energy difference between the two protons (middle), and opening angle between the two protons (bottom). Two separate simulations were performed using a ^{11}N ground state decay energy of 1.45 MeV and width of 2.4 MeV (left) and decay energy of 1.3 MeV and width of 990 keV (right).

The absence of a of di-proton emission in ^{12}O together with the ability to explain the ^{12}O data in a sequential decay model via a low lying state in ^{11}N serves as further evidence for an $s_{1/2}$ state between 700 keV and 1.45 MeV decay energy, far below the presently adopted value of 1.9 MeV.

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