The two-proton decay of ^{12}O and its isobaric analog state in ^{12}N

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This report abstracts the results from a recent experiment with a ^{13}O secondary beam, using neutron and proton knockout reactions to populate $^{12}O_{gs}$ and its isobaric analog state (IAS) in ^{12}N [1]. The two-proton decays of these states were detected and used to deduce the masses and limit the decay widths of these states. The two-proton decay of $^{12}N_{IAS}$ is the second example of two-proton decay where all one-nucleon emissions are either energy or isospin forbidden. The energy of $^{12}N_{IAS}$ was unknown prior to this work and finding it completed the A = 12 quintet. The energy for this state and a new mass for $^{12}O_{gs}$ allowed for a fit of the Isobaric Multiplet Mass Equation (IMME) which showed no evidence of isospin symmetry breaking.

The Texas A&M University K500 cyclotron delivered a primary beam of *E/A*=38 MeV ^{14}N of intensity 80 pnA. A secondary beam of 2000-4000 s^{-1} *E/A*=30.34 MeV ^{13}O was separated from the other reaction products using the MARS spectrometer. This secondary beam impinged on a 45.6 mg/cm^2 target of ^{9}Be. The beam and reaction products were incident on a 10 cm *x* 10 cm 300 *u*m Si ΔE detector of type TTT manufactured by Micron Semiconductor. This detector has 128 strips on both the front and back sides. The particles of interest pass through this Si detector, which was located 18 cm from target, and are stopped by a 32 element array of CsI(Tl) scintillator *E* detectors located immediately behind it. These CsI(Tl) detectors were arranged in a 6x6 array with the corner locations vacant.

In order to have confidence in the masses and widths, it is useful to compare to well-known "calibrations" states. Figs. 1(a) and 1(b) show the ^{12}N and ^{13}N excitation-energy spectra deduced with the invariant mass method for detected p+^{11}C and p+^{12}C events respectively. The first spectrum (a) is dominated by a peak corresponding to the first-excited state of ^{12}N which is produced very strongly in proton-knockout reactions. The peak in the second spectrum (b) can be associated with a known $J^\pi = 3/2^-$ level in ^{13}N. From Gaussian fits with suitable background, we obtain centroids of 968 keV and 3496 keV with a 2 keV statistical error for these two states. These can be compared to the tabulated values of 960±12 keV and 3502±2 keV, respectively, listed in the ENSDF database. From these comparisons we assign a systematic error of 10 keV to all our extracted excitation energies and mass excesses.

The reconstructed spectrum of total kinetic energy E_T released in the decay of ^{12}O is shown in Fig. 1(c) after a small background removal. Particle identification was obtained with the E-ΔE method, but complete separation of C isotopes was not achieved. The most important contribution to this problem is from channeling interactions in the Si ΔE detector which result in 5% of ^{11}C fragments leaking into the ^{10}C gate. (The MICRON TTT detectors are not cut off axis and thus channeling should be avoided in subsequent uses of this detector by mounting it so that particles are not incident normal its front surface.)

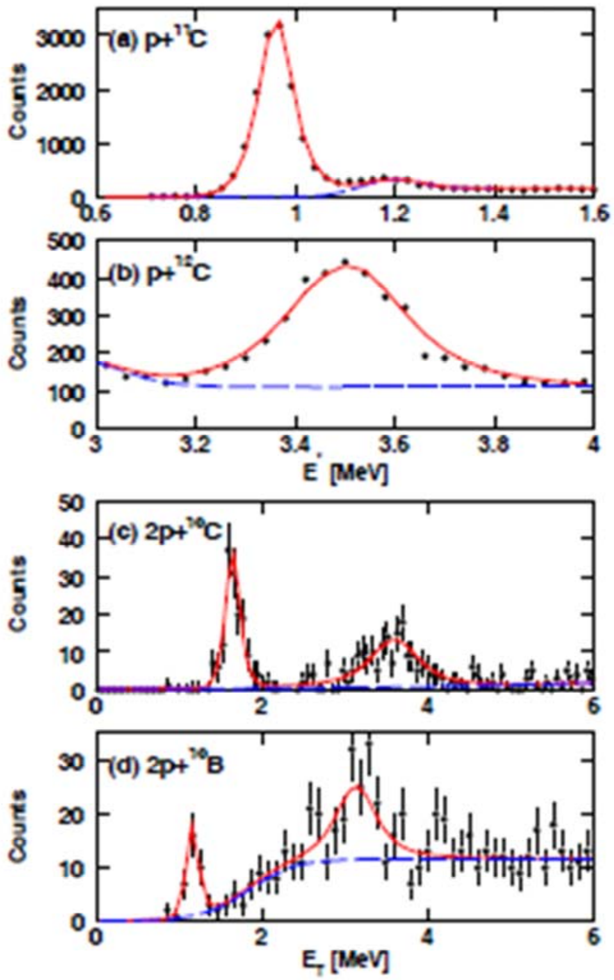

FIG. 1. Excitation-energy spectra of calibration peaks for (a) the 960-keV, $J^\pi = 2^+$ state in ^{12}N and (b) the 3.502 MeV, $J^\pi = 3/2^-$ level in ^{13}N. The solid curves show the results of Monte Carlo simulations of the peak shapes incorporating the detector response and the known level properties. The dashed curves indicate as estimation of the background under these peaks. Spectra of total kinetic energy released in the two-proton decay of (c) ^{12}O and (d) its analog in ^{12}N reconstructed from detected $2p+^{10}$C and $2p+^{10}$B events. The solid curves shows peak fits to these data with the dashed curves indicating the fitted background.

The solid curve in Fig. 1(c) shows a fit to the spectrum assuming Bret-Wigner line shapes for the ground and excited-state peaks and including the experimental resolution using the Monte Carlo simulations. The width of the ground-state peak was found to be consistent with the experimental resolution. An upper limit of 72 keV at the 3σ level was determined.

The ^{12}N E_T spectrum from $2p+^{10}$B events, shown in Fig. 1(d), displays a peak at 1.165 MeV corresponding to an excitation energy of 10.45 MeV if ^{10}B was formed in its ground state. In principle, the detected ^{10}B fragment could have also been formed in more than 4 excited states, and thus its excitation energy may be larger than 10.45 MeV. The two-proton decay of the isobaric analog state is expected to populate the 1.740 MeV ^{10}B state which subsequently decays by γ–ray emission, see Fig. 2(b). If the observed peak is the IAS, then the level energy would be 12.19 MeV, exactly at the energy expected by the IMME. A fit to this peak with an exponential background is shown by the solid curve in Fig. 1(d). The peak width is again consistent with the experimental resolution with an upper limit of $\Gamma <$ 110 keV at the 3σ level. No such narrow ^{12}N levels are known above E^*=10 MeV and it seems highly likely this is the isobaric analog state.

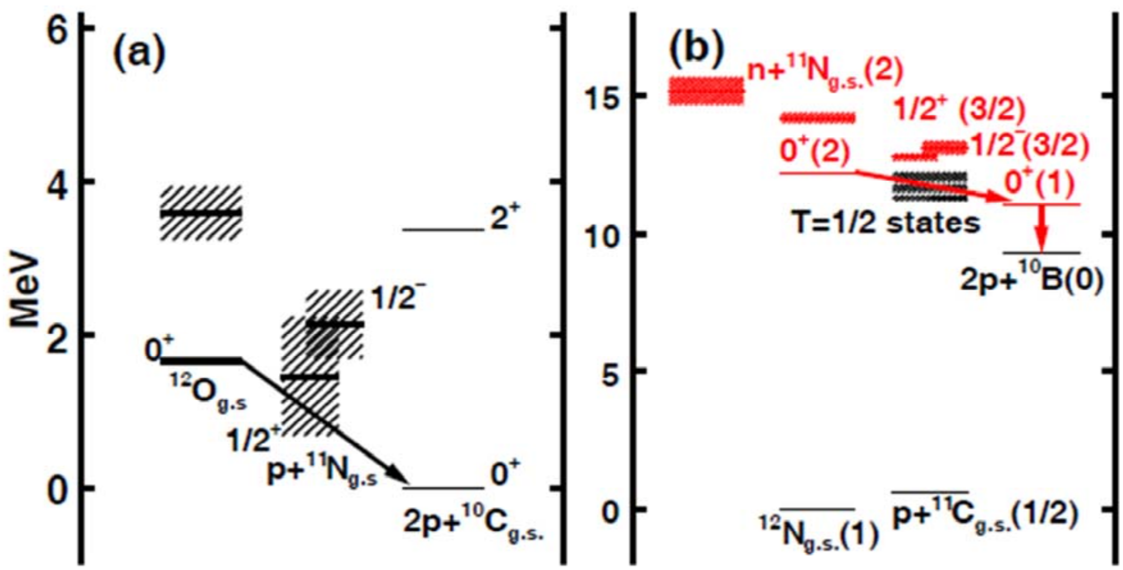

FIG. 2. Level diagrams showing the states of interest in the two-proton decays of (a) ^{12}O levels and (b) their isobaric analogs in ^{12}N. For the latter not all states are shown: The intermediate states that conserve isospin have their isospin indicated in the parenthesis (red). Also for 11C, the possible isospin violating T=1/2 intermediate states are indicated. The ^{11}N levels in both (a) and (b) are not well determined.

Having completed the quintet (see Ref. [1]) quadratic, cubic, and quartic fits to the IMME were done. The mass excesses are clearly consistent with the quadratic form of the IMME expected for isospin symmetry. The d coefficient for the cubic fit is 0.4±4.7 keV, a result consistent with zero. Although the IMME fits the data quite well this does not rule out all aspects of isospin asymmetries. For multiplets where the proton-rich members are at or near the continuum, the wavefunctions of the last proton extend further out compared to the analog neutrons in the bound neutron-rich members. This effect is enhanced for nucleons in s orbits where the effect is called the Thomas-Ehrman shift. These isospin asymmetries are mostly absorbed into the b and c coefficients of the IMME and produce very small d values.

In summary we have created ^{12}O fragments via neutron knockout from a ^{13}O projectile. The three decay products produced in the two-proton decay of the ground and an excited state were detected and the ^{12}O mass and width were determined with the invariant mass method. The width of the ground state was found to be less than 72 keV. The isobaric analog state of ^{12}O$_{gs}$ in ^{12}N was observed for the first time.

Single-nucleon decay of this state cannot conserve both energy and isospin but two-proton decay to the isobaric analog in ^{10}B does. Thus to the extent that isospin is conserved, this represents a Goldansky type two-proton decay of a type previously seen only once before – the isobaric analog of ^{8}C in ^{8}B. No evidence for isospin symmetry breaking was found in A = 12.

[1] M.F. Jager *et al.*, Phys. Rev. C. **86**, 011304(R) (2012).