Correlated two-proton decay from $^{10}C^*$

K. Mercurio,[1] R. J. Charity,[1] R. Shane,[1] L. G. Sobotka,[1] J. M. Elson,[1] M. Famiano,[2] A. Wuosmaa,[2]
A. Banu, C. Fu, L. Trache, R. E. Tribble, and A. M. Mukhamedzhanov
[1]*Washington University, St. Louis, Missouri 63130*
[2]*Western Michigan University, Kalamazoo, Michigan 49008*

Almost 50 years ago Goldansky [1] discussed the issue of correlated two-proton emission. Such decays can be reporters of initial-state correlations, much like α-decay informs us of the importance of α-clusters to the low-density energy-density functional [2]. No clear evidence of correlated two-proton (2p) emission was present in 1997 when Woods and Davids reviewed this subject [3]. Despite the recent flurry of activity near, at, and beyond the proton drip line, there is still no uncontested case of ^1S correlated 2p emission. The data on the known 2p cases indicate either sequential decay (e.g. ^{12}O), nearly uniform sampling of the 3-body phase space (e.g. $^6Be_{g.s.}$, ^{16}Ne, and ^{19}Mg) or 3-body with definite, but not ^1S, correlations from the parent structure (^{45}Fe). In this work we present evidence for a significant ^1S correlated-2p component in the decay of a state at E* = 6.6 MeV in ^{10}C. In contrast to this state, we show that a previously known state at E*=5.20 MeV and a previously unknown state at 8.4 MeV decay sequentially, while yet another at E*=5.30 MeV decays by uniformly sampling the 3-body phase space.

Last year, we presented a study of the continuum spectroscopy of ^{10}C [4]. The data from this (first) experiment provided only a weak suggestion of a 2p correlation in the decay of the state at 6.6 MeV. In the summer of 2007 we repeated this experiment, with an identical experimental set-up, but with 3 times the beam. This was achieved by using enriched Carborane ($C_2[^{10}B_{10}]H_{12}$) as a source material for the primary ^{10}B beam. The primary beam impinged on a hydrogen gas cell held at a pressure of two atmospheres and kept at liquid-nitrogen temperature. The secondary beam of E/A=10.7 MeV ^{10}C, with intensity of 2×10^5 s^{-1}, purity of 99.5%, an energy spread of 3%, and a spot size of 3.5x3.5 mm was produced with the MARS spectrometer. Both 14.1 mg/cm² Be and 13.4 mg/cm² C secondary targets were used.

The two, three and four-body correlations are shown in Fig. 1 as excitation energy spectra (by subtracting the Q-value from the center-of-mass energies.) In addition to the decay paths found in our previous work, a previously unobserved (broad) state at E*=8.4 MeV is found that decays to ^9B(E*=2.36 MeV). For this report we focus on the correlations between the protons in the decay of both the 5.30 and 6.6 MeV states that 1) bypass the $^9B_{g.s.,}$ but 2) possess the 2α correlation indicating that $^8Be_{g.s}$ was an intermediate. The relative emission angle θ_{rel} between the two protons in the 2α+2p center of mass and relative energy E_{rel} of the protons are shown in Fig. 2. What is most striking is the symmetry and lack of symmetry about θ_{rel} =90° for the data from the states at 5.30 and 6.6 MeV, respectively. While angular momentum will generate correlations between successively emitted particles, θ_{rel} distributions must remain symmetric about θ_{rel} =90°. The shapes of the E_{rel} distributions are also markedly different for the two cases. The distribution from the 5.30 MeV state is broad with only a weak enhancement at low energy, while the distribution for the 6.6 MeV state is strongly enhanced at low energy.

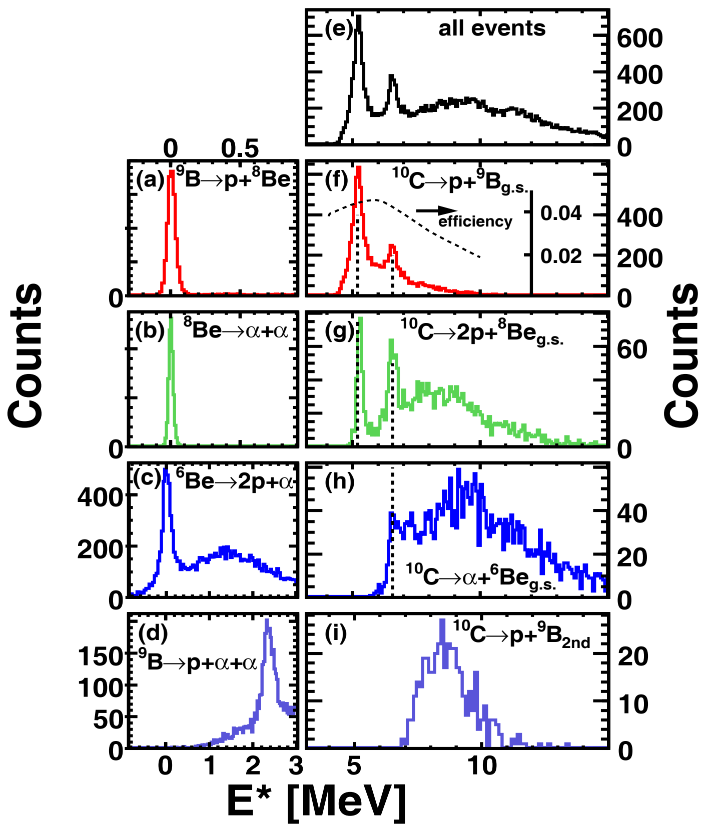

Figure 1. (Color online) Reconstructed excitation energies from two and 3-body correlations (left, a-d) and 4-body correlations (right, e-i). Panels (c) and (d) exclude events with the $^{8}B_{g.s.}$ correlation. The p + $^{9}B_{g.s.}$ detection efficiency is included, with an internal axis, in panel f.

A number of simulations were performed to evaluate which processes contribute to these decays. The first simulation assumed a sequential two-proton decay passing through the wide E*=1.5 MeV first excited state of ^{9}B. In the second simulation, the 3-body phase space of the two protons and the $^{8}Be_{g.s.}$ fragment is uniformly sampled. The results of these simulations are shown in Fig. 2. Both the sequential and 3-body simulations come close to reproducing the θ_{rel} and E_{rel} distributions from the 5.30 MeV state, although the 3-body simulation is somewhat better. On the other hand, for the 6.6 MeV state, neither simulation can reproduce either the asymmetry about 90^{o} in θ_{rel} or the low-energy enhancement observed in the E_{rel} spectrum.

In order to break the symmetry about 90^{o}, we included a 2p correlation, of the type originally imagined by Goldansky, but heretofore never observed. Both an R-matrix scheme, using an ^{1}S p-p phase shift for an imagined intermediate, and a Faddeev calculation, where the nuclear p-p scattering amplitude is dominated by the ^{2}He resonance, largely reproduce the correlations found between the two protons from the decay of the 6.6 MeV state. It is possible that this is a rotational state built on a single-particle structure well described as almost pure $(sd)^2$. (Two excited protons alone in the sd shell.) The analog is known in ^{10}Be, but particle bound.

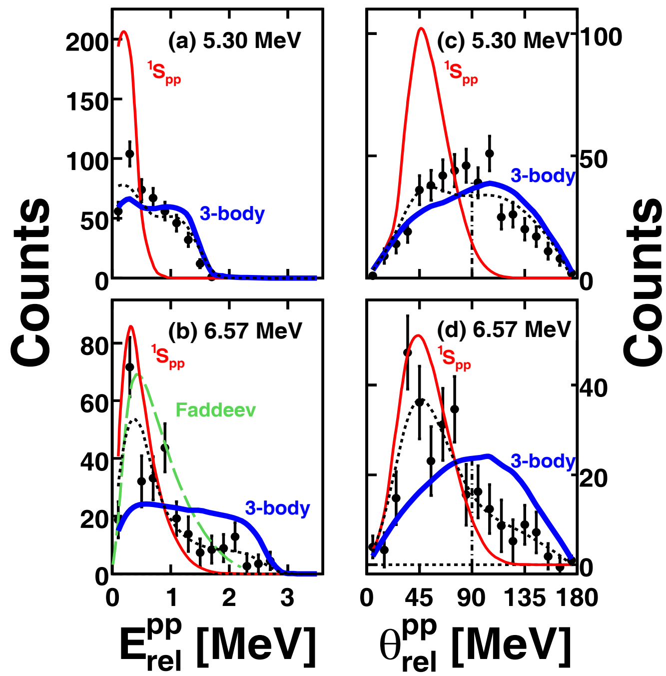

Figure 2. Energy (left) and angle (right) p-p correlations for the 5.30 (top) and 6.6 MeV (bottom) structures. The data are the combined data from the present and previous experiments. Simulations for decay uniformily spanning the full 3-body phase space (thick lines) and correlated 2p emission calculated using the R-matrix formalism (thin lines) are shown. The dotted lines are mixtures of 3-body and correlated (85:15 and 35:65 for the 5.30 and 6.6 MeV states, respectively.) The dashed line (b) is a Faddeev calculation.

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