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Correlated two-proton decay from ^{10}C

K. Mercurio,[1] R. J. Charity,[2] R. Shane,[1] L. G. Sobotka,[1,2] J. M. Elson,[2] M. Famiano,[3] A. H. Wuosmaa,[3] A. Banu,[4] C. Fu,[4] L. Trache,[4] R. E. Tribble,[4] and A. M. Mukhamedzhanov[4]
[1]*Departments of Physics, Washington University, St. Louis, Missouri 63130, USA*
[2]*Departments of Chemistry, Washington University, St. Louis, Missouri 63130, USA*
[3]*Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008, USA*
[4]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*

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The decay of ^{10}C excited states to the $2p + 2\alpha$ exit channel has been studied using inelastic excitation of a secondary ^{10}C beam. The decay sequences leading to the $2p + 2\alpha$ final state are determined for the previously known levels and for a newly found level at $E^* = 8.4$ MeV. A state at $E^* = 6.57$ MeV is shown to undergo two-proton decay to ^{8}Be$_{g.s.}$ with strong p-p correlations consistent with the ^{1}S phase shift. Based on the lack of such correlations for other two-proton decays, this indicates that the correlations are associated with structure of the parent level.

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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]. Recently Blank and Płoszajczak have reviewed $2p$ emission [3]. Excellent cases for sequential decay (e.g., ^{12}O [4]) and nearly uniform sampling of three-body phase space (e.g., ^{6}Be$_{g.s.}$ [5–7], ^{16}Ne, ^{19}Mg [8,9], and ^{45}Fe [10]) exist. The ^{45}Fe case is a beautiful example of the single-particle orbital angular momentum of the protons in the parent being impressed on the three-body dynamics [10]. On the other hand, the evidence for ^{1}S correlated $2p$ emission is poor. One of the cases for potential ^{1}S correlated $2p$ emission is that of the decay of the total strength above $E^* = 3.7$ MeV in ^{17}Ne [11]. Aside from the fact that the parent excitation is not well determined, the proton-proton relative energy spectrum does not peak at small energies as expected for ^{1}S decay. The case for significant ^{1}S decay from a state at $E^* = 6.15$ MeV in ^{18}Ne (a case orginally studied by del Campo *et al.* [12]) has been very recently presented by Raciti *et al.* [13]. While these data are also suggestive of ^{1}S $2p$ emission, the statistical significance is marginal and, as the parent state is not well resolved, the background makes an uncertain contribution to the observed correlations.

Here we present the case for a significant ^{1}S correlated $2p$ decay component from a state imbedded in a well-resolved structure at $E^* = 6.57$ MeV in ^{10}C. At the same time, 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 nearly uniformly sampling the three-body phase space.

In 2007 we presented results from our initial experiment studying the continuum spectroscopy of ^{10}C [14]. This initial experiment provided a weak suggestion of a $2p$ correlation in the decay of a state at 6.57 MeV. We repeated the experiment, tripling the statistics, and it is the combined results that we now present. Since the reporting of our initial work, Curtis *et al.* [16] have investigated ^{10}C states via inelastic scattering at $E/A = 30$ MeV [15]. Their work suggests a level at 4.2 MeV, which they speculate is the long sought after excited 0_2^+ state.

The decay scheme of ^{10}C is shown in Fig. 1. Only the ground state and the first-excited state (2^+, $E^* = 3.351$ MeV) are particle bound. The threshold for $^{10}\mathrm{C} \rightarrow 2p + 2\alpha$ decay is $E^* = 3.726$ MeV, while the binary decay threshold to particle stable products, $^{10}\mathrm{C} \rightarrow {}^3\mathrm{He} + {}^7\mathrm{Be}$, is $E^* = 15.0$ MeV. Thus, all excited states with excitation energies between these thresholds must decay, in some manner, to the $2p + 2\alpha$ exit channel. The evidence for the decay scenarios shown in Fig. 1 and the p-p correlations for the nonsequential decay steps are presented in this work.

The Texas A&M University K500 cyclotron facility was used to produce 200 pnA of ^{10}B at $E/A = 15.0$ MeV. Enriched carborane ($C_2[^{10}B_{10}]H_{12}$) was used as the source material. The primary beam impinged on a hydrogen gas cell held at a pressure of two atmospheres and kept at liquid-nitrogen temperature. A secondary beam of $E/A = 10.7$ MeV ^{10}C was produced through the $^{10}\mathrm{B}(p, n)^{10}\mathrm{C}$ reaction and separated from other reaction products using the MARS spectrometer [17]. This secondary beam, with intensity of $2 \times 10^5 s^{-1}$, purity of 99.5%, an energy spread of 3%, and a spot size of 3.5×3.5 mm, was used with both 14.1 mg/cm^2 Be and 13.4 mg/cm^2 C targets. The C target was contaminated with H_2O and interactions with the hydrogen component produced a sizable background in the $2p + 2\alpha$ events above $E^* \sim 5.5$ MeV. Thus the C target data were only used to verify the Be target results for the decay paths of the states below this excitation energy.

Charged particles were detected and identified in four Si E-ΔE telescopes located in a plane 14.0 cm downstream of the target. The telescopes, part of the HiRA array [18], consisted of a 65-μm-thick, single-sided Si-strip ΔE detector followed by a 1.5-mm-thick, double-sided Si strip E detector. All Si detectors were 6.4×6.4 cm in area with the position-sensitive faces divided into 32 strips. The telescopes were positioned in a square arrangement with each telescope offset from its

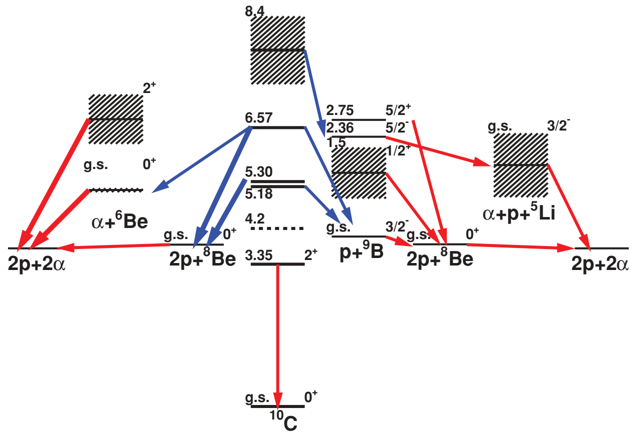

FIG. 1. (Color online) Level scheme and decay paths for ^{10}C.

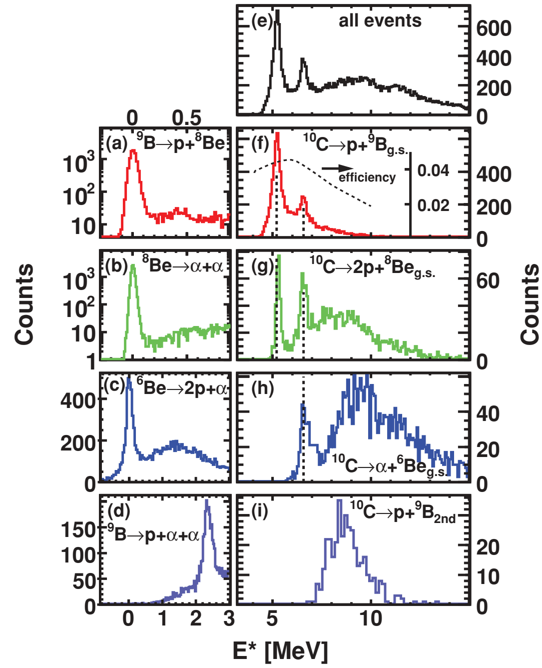

FIG. 2. (Color online) Reconstructed excitation energies from two- and three-body correlations (left side, a–d) and four-body correlations (right side, e–i). Panels (c) and (d) exclude events with the ^{8}Be$_{\rm g.s.}$ correlation. The $p +^9$ B$_{\rm g.s.}$ detection efficiency is included, with an internal axis, in panel (f).

neighbor to produce a small, central, square hole through which the unscattered beam passed. With this arrangement, the angular range from $\theta = 5$ to 33° was covered. Signals produced in the telescopes were read out with the HINP16C chip-readout electronics [19].

Energy calibrations were obtained from ^{228}Th α-source data, the p, d, and α-particle "punch through" energies, and the energies of well-known resonances. Monte Carlo simulations were performed to correct for energy losses and small-angle scattering [20] in the target and to model the primary energy and angular distributions of the parent fragments. The experimental widths, as well as centroids, of the ^{6}Li($E^* = 2.19$ MeV, $d + \alpha$) and two resonances in ^{12}C($E^* = 7.65$ and 9.64 MeV, 3α) were reproduced by these Monte Carlo simulations.

Two- and three-body subsets of the four-body ($2p + 2\alpha$) events were analyzed, and the excitation energies of the potential ^{10}C decay intermediates are shown in the left-hand side of Fig. 2. Excitation energies of the potential intermediates were generated from the relative energy of the set of particles in their center-of-mass frame minus the decay Q value. For cases such as $p + 2\alpha$ where there are two possible subsets of each event, only the subset with the smallest excitation energy is included in Fig. 2. The intermediate correlations shown are (a) ^{9}B $\to$ ^{8}Be$_{\rm g.s.} + p$, (b) ^{8}Be $\to \alpha + \alpha$, (c) ^{6}Be $\to p + p + \alpha \cap$ no ^{8}Be$_{\rm g.s.}$, and (d) ^{9}B $\to p + \alpha + \alpha \cap$ no ^{8}Be$_{\rm g.s.}$ correlations. The widths of the intrinsically narrow ^{8}Be$_{\rm g.s.}$ and ^{9}B$_{\rm g.s.}$ resonances ($\Gamma = 5.57$ eV and $\Gamma = 0.54$ keV, respectively) are totally determined by the detector response. The peaks corresponding to ^{6}Be$_{\rm g.s.}$($\Gamma = 92$ keV) and ^{9}B$_{\rm 2nd}$($E^* = 2.361$ MeV, $\Gamma_{2.345} = 81$ keV) are well resolved.

The reconstructed ^{10}C excitation spectrum of all $2p + 2\alpha$ events is shown in Fig. 2(e). The peaks at 5.2–5.3 and approximately 6.57 MeV have widths (FWHM $\geqslant 320$ keV) well in excess of the simulated detector response (180 and 240 keV for these energies, respectively) and thus they are truly wide resonances or multiplets. Strength at these two energies has been known for decades [21–25] and the mirror nucleus ^{10}Be [26] has a quadruplet (2^+, 1^-, 0^+ and 2^-) and a doublet (3^- and 2^+) at the corresponding energies. While these multiplets, if excited, are not resolved, they are potentially separable by their decay mechanism.

Figure 2(f) displays the reconstructed ^{10}C spectrum when the decay is through the narrow ^{9}B$_{\rm g.s.}$ while Fig. 2(g) displays the spectrum when the ^{8}Be$_{\rm g.s.}$ correlation is present but the ^{9}B$_{\rm g.s.}$ correlation is absent. Approximately 90% of the strength near 5.20 MeV is found to decay through ^{9}B$_{\rm g.s.}$. The remaining strength in this region is at slightly higher energy (5.30 MeV), of narrower width, and bypasses ^{9}B$_{\rm g.s.}$. This confirms the original claim by Schneider *et al.* [27] that this structure is at least a doublet. The higher-energy component (5.30 MeV) implies a state that proton decays through the tail of the wide ^{9}B$_{\rm 1st}$ (not truly sequential as the intermediate has a width comparable to the decay energy), "pseudo" two-body with some $2p$ correlation, or by uniformly sampling the three-body phase space.

The strength near $E^*(^{10}\text{C}) = 6.57$ MeV is found to decay through three paths: sequential proton decay to ^{9}B$_{\rm g.s.}$ [Fig. 2(f)], bypassing ^{9}B$_{\rm g.s.}$, i.e., direct $2p$ decay to ^{8}Be$_{\rm g.s.}$ [Fig. 2(g)], and via ^{6}Be$_{\rm g.s.}$ as an intermediate [Fig. 2(h)]. The gate for the latter excludes the ^{8}Be$_{\rm g.s.}$ and ^{9}B$_{\rm 2nd}$ correlations. Again, the $2p$ decay directly to ^{8}Be$_{\rm g.s.}$, without the ^{9}B$_{\rm g.s.}$ correlation, implies one of the scenarios mentioned for the decay of the state at 5.30 MeV.

A state at $E^* = 4.2$ MeV is claimed in Ref. [15]. We find no evidence for this state with either target. The dashed line in Fig. 2(f) shows our $p + {}^9$B$_{\rm g.s.}$ efficiency, which does not drop off significantly until below 4 MeV. If excited, such a state would have been observed.

The $E^*(^9\text{B}) - E^*(^{10}\text{C})$ correlation, plotted in Fig. 3, shows a previously unobserved state at $E^* = 8.4$ MeV that decays

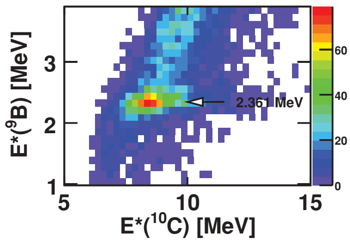

FIG. 3. (Color online) Three-particle ($\alpha\alpha p$) versus four-particle energy correlations showing a new state in ^{10}C at $E^* = 8.4$ MeV that decays through the 2.361 MeV state in ^{9}B.

to ^{9}B$_{2nd}$. The projection, shown in Fig. 2(i), indicates that this state has a width of approximately 2 MeV.

We now consider the correlations between the protons in the decay of both the 5.30 and 6.57 MeV states that (1) bypass the ^{9}B$_{g.s.}$ but (2) possesses the 2α correlation indicating that ^{8}Be$_{g.s.}$ was an intermediate. The relative energy E_{rel}^{pp} of the protons and the relative emission angle θ_{rel}^{pp} between the two protons in the $2\alpha + 2p$ center of mass are shown in Fig. 4. [The background for the correlations from the 6.57 MeV state was constructed from contributions from either side of the prominent peak, see Fig. 2(g).] What is most striking is the symmetry and lack of symmetry about $\theta_{rel}^{pp} = 90^\circ$ for the data from the states at 5.30 and 6.57 MeV, respectively. While angular momentum will generate correlations between successively emitted particles, θ_{rel}^{pp} distributions must remain symmetric about $\theta_{rel}^{pp} = 90^\circ$ [28]. The detector response (included in the simulations) induces only minor distortions [14]. The shapes of the E_{rel}^{pp} distributions are also markedly different for the two cases. The distribution from the 5.30 MeV state is broad with almost no enhancement at low energy, while the distribution for the 6.57 MeV state is significantly enhanced below $E_{rel}^{pp} = 1$ MeV.

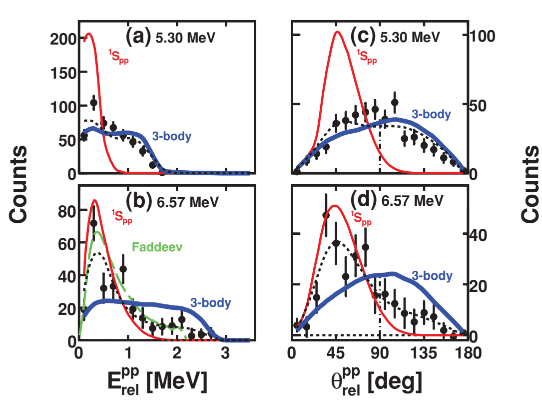

FIG. 4. (Color online) Energy (left) and angle (right) p-p correlations for the 5.30 (top) and 6.57 MeV (bottom) structures. The data are the combined data from the present and previous [14] experiments. Simulations for decay uniformly spanning the full three-body phase space (thick lines) and correlated $2p$ emission calculated using the R-matrix formalism (thin lines) are shown. The dotted lines are mixtures of three-body and correlated (85:15 and 35:65 for the 5.30 and 6.57 MeV states, respectively.) The dashed line (b) is the Faddeev calculation discussed in the text.

We first consider simulations for sequential two-proton decay passing through the wide $E^* = 1.5$ MeV first-excited state of ^{9}B and three-body decay uniformly sampling the full phase space of the two protons and the ^{8}Be$_{g.s.}$ fragment [29]. Both the sequential (see [14] for this simulation) and the three-body phase space [see Figs. 4(a) and 4(c)] simulations come close to reproducing the θ_{rel}^{pp} and E_{rel}^{pp} distributions from the 5.30 MeV state, although the three-body simulation is somewhat better. On the other hand, for the 6.57 MeV state, neither simulation can reproduce either the asymmetry about 90° in θ_{rel}^{pp} or the low-energy enhancement observed in the E_{rel}^{pp} spectrum.

To break the symmetry about 90° in θ_{rel}^{pp}, we performed calculations incorporating the ^{1}S $2p$ correlation. First, we followed the R-matrix approach used by Kryger *et al.* [4]. The line shape, in terms of the total decay energy E and E_{rel}^{pp}, is given by a Breit-Wigner with partial width $\Gamma_1(E, E_{rel}^{pp}) = 2\theta_1^2\gamma_1^2 P_l(E - E_{rel}^{pp})\rho(E_{rel}^{pp})$, where θ_1^2 and γ_1^2 are the spectroscopic factor and reduced width (associated with "^{2}He" emission), $P_l(E - E_{rel}^{pp})$ is the penetrability (calculated from the regular and irregular Coulomb wave functions), and the density of states $\rho(E_{rel}^{pp}) \propto \sin^2\delta(E_{rel}^{pp})/C^2E_{rel}^{pp}$ with δ the ^{1}S p-p phase shift and $C = \eta/(e^{2\pi\eta} - 1)$, where η is the Sommerfeld parameter.

We also executed the Faddeev logic [30] where the total decay amplitude is given by $R = R^{12} + R^{13} + R^{23}$, where R^{ij} is the component that contains the final-state interactions between particles i and j where the index 1 indicates the residue and 2 and 3 indicate the protons. The R^{23} amplitude is given by $R^{23} = (R^{12} + R^{13})G_{23}^{(0)}f_{23}$, where $G_{23}^{(0)}$ is the free Green's function of two protons and f_{23} is the half-off-the-energy shell (HOES) p-p scattering amplitude (taken as the sum of the HOES Coulomb scattering amplitude plus the HOES Coulomb-modified nuclear p-p scattering amplitude calculated for the s-wave first-rank Yamaguchi separable potential [31].) Because we do not know the explicit form of R^{12} and R^{13}, we replaced them by the Coulomb-centrifugal barrier penetration factor. The ^{8}Be-"^{2}He" relative orbital angular momentum is taken to be 2 (see below.) The full calculations [dashed line in Fig. 4(b)] does not differ significantly from a simplified calculation (not shown) based on using only the resonant part of the Coulomb modified nuclear p-p scattering amplitude, which is dominated by the "^{2}He" resonance [32].

The simulations that include the correlations expected from the ^{1}S p-p phase shift can reproduce both the angular asymmetry and the low-energy enhancement seen in the decay of the state at 6.57 MeV. The R-matrix approach does require a significant admixture of the three-body phase space to get the larger values of E_{rel}^{pp} and θ_{rel}^{pp} [dashed lines in Figs. 4(b) and 4(d), see caption]. The nonobservance of similar correlations in the three-body decay of ^{6}Be$_{g.s.}$ [5] or the decay of the 5.30 MeV state in ^{10}C suggests that the observed $2p$ correlations from the decay of the 6.57 MeV state are not simply a final-state interaction acting on a uniformly sampled three-body phase-space distribution. Such correlations would be present in any nonsequential $2p$ decay. Therefore, the $2p$ correlation observed for decay of the 6.57 MeV state must be a reflection of the structure of the decaying state.

In this energy region, the mirror nucleus ^{10}Be has two states: 3^- and 2^+. The second is thought to be a collective rotation built on 0_2^+ (a state in the lower quadruplet). Microscopic four-cluster [33] and antisymmetrized molecular dynamics [34] indicate that this 0_2^+ level (well known in ^{10}Be and long sought in ^{10}C) is well described by an almost pure $(sd)^2$ character. Strong ^{1}S correlations between protons in the analog ^{10}C state and any rotational states built on this band-head, such as the 2^+, are to be expected. We point out that if the peak observed at 4.2 MeV by Curtis *et al.* [15] were the 0_2^+ band head, it is 0.8 MeV too low to be consistent with the analysis of Fortune and Sherr [16]. Barker [35] has also concluded that a state at 4.2 MeV is unlikely to be the 0_2^+ state [35].

We have reported on the decay of the particle-unbound states in ^{10}C between $5 < E^*(\text{MeV}) < 10$ MeV. In addition to the known doublet at 5.20–5.30 MeV and the state or states at 6.57 MeV, we report a new wide resonance at 8.4 MeV. The state (or states) at (or near) 6.57 MeV exhibit two-body decay through ^{9}B$_{\text{g.s.}}$ and ^{6}Be$_{\text{g.s.}}$ intermediates and a three-body component that explores only a subset of the full three-body phase space. This subset provides strong evidence for a decay with significant ^{1}S proton-proton correlations. Decays such as this present a reflection of ^{1}S correlations in the parent as does knock-out work, e.g., ^{16}O$(e, e'pp)^{14}$C$_{\text{g.s.}}$ [36]. The connection between knock-out and decay studies, as concerns spectroscopic strength and the effects of short-range correlations, is a promising area for future work.

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