β-Delayed Proton Decay of ^{9}C†

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The delayed-proton spectrum following the β decay of ^{9}C ($\tau_{1/2} = 126.5 \pm 1.0$ msec) was found to consist primarily of a continuum extending from 13 to 1.5 MeV, the latter being the lowest energy observed. In addition to the previously observed peaks at 9.28 and 12.30 MeV (c.m.), *possible* peaks between 3 and 7 MeV have been tentatively identified.

Our recent paper[1] concerning the β-delayed-proton precursors ^{17}Ne and ^{33}Ar mentioned the observation of ^{9}C, also a precursor, but contained no details of its proton spectrum. Previously, Hardy *et al.*[2] had observed the decay of ^{9}C to result in two high-energy proton peaks riding on a continuum. However, they could not have observed protons much below 3 MeV because of the thickness of the first counter of their telescope. In addition, the proton data of Ref. 2 contain an unknown contribution from β- and γ-ray background which might have been significant at the lower energies.

Observation of peaks in the delayed-proton spectrum of ^{9}C would be of particular interest since they would correspond to levels in ^{9}B, many of which are still not well characterized.[3] These levels, in particular those of negative parity, could be compared to the predictions of intermediate-coupling calculations,[4] which have proved quite successful elsewhere in the $1p$ shell. Fortunately, β decay from ^{9}C should preferentially populate such levels, since ^{9}C should have $J^{\pi} = \frac{3}{2}^{-}$, as does its mirror ^{9}Li.

The methods of target preparation, activity transport, particle identification, and data collection were described in detail previously.[1,5] Oxygen swept the ^{9}C (produced via the reaction $^{10}B(p, 2n)^{9}C$ using an external 43-MeV proton beam from the Berkeley 88-in. cyclotron) to a shielded counting chamber. β-delayed protons were detected by a counter telescope consisting of either a 14- or a 50-μm phosphorous-diffused silicon ΔE counter and a 1.5-mm lithium-drifted silicon E counter; particle identification was performed by a Goulding-Landis identifier. As is illustrated in Ref. 5, these experiments have negligible background arising from β-particle pileup.

Figures 1 and 2 show proton spectra following the β decay of ^{9}C; these were obtained with counter telescopes employing the 50- and 14-μm ΔE detectors, respectively. In both figures, peaks are labeled with proton energies in the c.m. system. The bracketed energies refer to possible peaks above the continuum for which assignments are less certain. This activity decayed with a half-life of 126.5 ± 1.0 msec; this half-life agrees well with earlier work[2,6] and results in an average value of 126.5 ± 0.9 msec. Any contribution to the spectrum from ^{13}O, produced from a possible nitrogen contaminant in the sweeping gas, is eliminated by its short half-life, 9 msec, since counting began about 100 msec after the gas was swept past the target.

The peak energies were determined by calibrating the three higher energy peaks against the known[1] spectrum of ^{17}Ne (produced via the reaction $^{16}O(^{3}He, 2n)^{17}Ne$ using data taken with the 50-μm ΔE counter. These peaks were then used to calibrate the data taken with the thinner ΔE counter. Lines on both Figs. 1 and 2 show the continuum levels assumed in the extraction of peak widths and energies. Both spectra show similar evidence for a 6.10-MeV (c.m.) proton group. Further, Fig. 2 presents reasonable evidence for an additional

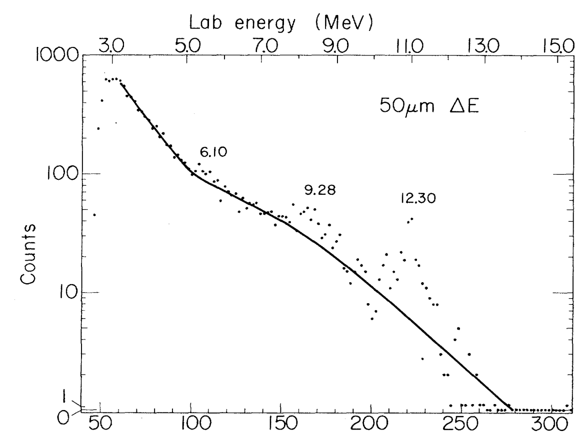

FIG. 1. Spectrum of delayed protons following the β decay of ^{9}C. A counter telescope employing a 50-μm ΔE detector was used.

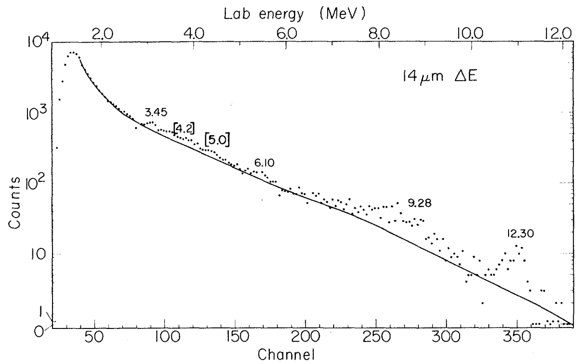

FIG. 2. Spectrum of delayed protons following the β decay of ^{9}C as measured in a counter telescope employing a 14-μm ΔE detector. Protons with laboratory energies *above* ~8.0 MeV were not reliably detected in this telescope because of their small energy loss in this thin ΔE detector. Energies in brackets denote possible peaks above the continuum.

group at 3.45 MeV plus weaker indications of two groups at 4.2 and 5.0 MeV.

Table I lists the energies corresponding to all of the possible indications of peaks in the proton spectra, and tentatively correlates them with known[3] states in ^{9}B. The possible 5.0-MeV proton group has been assumed to result from decay of the positive-parity state at 4.85 MeV. β-decay to this state is first forbidden and therefore would not be expected to be readily observable. However, the logft values for allowed β decays in the mirror nucleus, ^{9}Li, are known[7] to range from 5 to 6, while first-forbidden transitions in ^{15}C and ^{11}Be have only slightly larger logft values, ranging from 6 to 6.8. Furthermore, α-p coincidence experiments[8] in which ^{9}B was populated in the reaction ^{10}B(^{3}He, α)^{9}B indicate that the 2.80-MeV state ($J^\pi = \frac{3}{2}^+, \frac{5}{2}^+$) in ^{9}B decays almost entirely via proton emission to the ground state of ^{8}Be, while the 2.33-MeV state ($J^\pi = \frac{5}{2}^-, \frac{1}{2}^-$) has less than a 0.5% branch via this channel. This selectivity in decay channel, if characteristic of all low-lying states, could make it possible to detect protons from a positive-parity level even if its feeding from β decay were rather weak. Similarly, the unassigned 6.10-MeV proton group may follow the decay of an unknown positive-parity state also formed via first-forbidden β decay.

The 3.45-MeV proton group could result from decay of a ^{9}B state at 3.2 MeV. In fact, intermediate-coupling calculations[4] predict a hitherto unobserved $J^\pi = \frac{3}{2}^-$ state at about 4.6 MeV but do not provide a precise estimate for the strength of the β decay to this state. Predictions[4] of the ft value range over two orders of magnitude, depending on the parameters used in determining the wave functions. Even though Clough *et al.*[3] have tentatively assigned $J^\pi = \frac{3}{2}^-$ to a level at 3.2 MeV, the existence of a state at this energy has not been definitely established.[3,9] Though further work is clearly necessary, our data are consistent with a state at 3.2 MeV.

The strong proton continuum probably results from several sources. First, the levels of ^{9}B are quite broad, as is the first excited state of ^{8}Be(1.4 MeV), so the combination of many broad peaks tends to produce a featureless spectrum. Second, a level in ^{9}B may emit an α particle resulting in an extremely broad distribution of proton energies. Finally, there may be some contribution to the continuum from direct three-body decay. The existence of a large continuum and the suggestion from the work of Wilkinson, Sample, and Alburger[8] that those states fed most strongly in β decay may prefer to decay via ^{5}Li + α preclude the determination of ft values from the peak intensities in the delayed-proton spectrum.

TABLE I. Delayed protons following the β decay of ^{9}C($J^\pi = \frac{3}{2}^-$).

Proton energy [a] (MeV)	Γ [b] (keV) [a]	Corresponding state in ^{9}B (MeV): If decaying to ^{8}Be(g.s.)	If decaying to ^{8}Be(2.9 MeV)	Known state (MeV)	J^π
3.45 ± 0.25	200 ± 100	3.26 ± 0.25	c	(3.2)	($\frac{3}{2}^-$)
(4.2 ± 0.3) [d]	1000 ± 200	4.0 ± 0.3	6.9 ± 0.3	4.05	($\frac{5}{2}^-$)
(5.0 ± 0.2) [d]	400 ± 200	4.8 ± 0.2	c	4.85	($\frac{3}{2}, \frac{5}{2})^+$
6.10 ± 0.10	400 ± 100	5.91 ± 0.10	c		
9.28 ± 0.24 [e]	1800 ± 200	9.09 ± 0.24	11.99 ± 0.24	12.06	($\frac{1}{2}, \frac{3}{2})^-$
12.30 ± 0.10 [e]	450 ± 100	12.11 ± 0.10	c	12.06	($\frac{1}{2}, \frac{3}{2})^-$

[a] Energies and widths are given in the c.m. system.
[b] The width given is the full width at half maximum.
[c] The relatively narrow width indicates that this proton group does not lead to the first excited state of ^{8}Be (Γ=1.4 MeV).
[d] Weaker evidence for possible groups at these energies was observed.
[e] The ratio of the intensities of the 9.28- and 12.30-MeV groups is 1.2 ± 0.2.

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[1]J. C. Hardy, J. E. Esterl, R. G. Sextro, and J. Cerny, Phys. Rev. C 3, 700 (1971).

[2]J. C. Hardy, R. I. Verrall, R. Barton, and R. E. Bell, Phys. Rev. Letters 14, 376 (1965).

[3]K. Gul, B. H. Armitage, and B. W. Hooton, Nucl. Phys. A153, 390 (1970); A. S. Clough, C. J. Batty, B. E. Bonner, and L. E. Williams, Nucl. Phys. A143, 385 (1970); and references therein.

[4]S. Cohen and D. Kurath, Nucl. Phys. 73, 1 (1965); F. C. Barker, Nucl. Phys. 83, 418 (1966).

[5]J. E. Esterl, R. G. Sextro, J. C. Hardy, G. J. Ehrhardt, and J. Cerny, Nucl. Instr. Methods 97, 229 (1971).

[6]J. M. Mosher, R. W. Kavanagh, and T. A. Tombrello, Phys. Rev. C 3, 438 (1971).

[7]Y. S. Chen, T. A. Tombrello, and R. W. Kavanagh, Nucl. Phys. A146, 136 (1970).

[8]D. H. Wilkinson, J. T. Sample, and D. E. Alburger, Phys. Rev. 146, 662 (1966).

[9]J. D. Anderson, C. Wong, B. A. Pohl, and J. W. McClure, Phys. Rev. C 2, 319 (1970); and R. J. Slobodrian, H. Bichsel, J. S. C. McKee, and W. F. Tivol, Phys. Rev. Letters 19, 595 (1967).

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Comment on a Possible $J^\pi = 0^+$, $T = 2$ Resonance in $Be^9(He^3, \gamma\gamma)C^{12}$†

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The reaction $Be^9(He^3, \gamma\gamma)C^{12}$ has been reexamined near a previously reported resonance at $E_{He^3} = 1.739 \pm 0.007$ MeV, which was ascribed to the lowest $T=2$ state in C^{12}. No resonance was observed and an upper limit $\Gamma_{He^3}\Gamma_\gamma/\Gamma < 1.5$ meV is established for the $T=2$ resonance strength (assuming $\Gamma \le 1.5$ keV) which is $\frac{1}{5}$ of the previously reported strength.

Several unsuccessful efforts have been made in recent years to observe the lowest $T=2$ level in C^{12} as an isospin-forbidden resonance in proton[1] and deuteron[2]-induced reactions. This level is known to have an excitation energy $E_x = 27.595 \pm 0.020$ MeV from a $C^{14}(p, t)C^{12}$ measurement.[3,4] Recently Black, Caelli, and Watson[2] reported the observation of a strong candidate for this level as a resonance in the reaction $Be^9(He^3, \gamma\gamma)C^{12}$ at an excitation energy of 27.585 ± 0.005 MeV corresponding to a bombarding energy of 1.739 ± 0.007 MeV. An upper limit of $\Gamma < 1.5$ keV for the total width and a value for the capture strength of $\Gamma_{He^3}\Gamma_\gamma/\Gamma = 8 \pm 5$ meV were given. We present the results of a reinvestigation of the same reaction in the region $E_{He^3} = 1.721$ to 1.764 MeV, in which no resonance was observed.

In this experiment, thin metallic Be^9 targets evaporated on polished Au backings were bombarded with the $He^{3(+)}$ beam of the Brookhaven National Laboratory 3.5-MV Van de Graaff accelerator, and high-energy γ rays were detected in a 10×10-in. NaI(Tl) detector at 0°. The accelerator beam analyzing magnet was calibrated by use of the resonance $Mg^{24}(\alpha, \gamma)Si^{28}$ at $E_\alpha = 3.1998 \pm 0.0010$ MeV,[5] the $C^{13}(p, \gamma)N^{14}$ resonance at $E_p = 1.7476 \pm 0.0009$ MeV,[6] and the $Be^9(p, \gamma)B^{10}$ resonance at 1.0832 ± 0.0004 MeV.[7] The internal consistency of the various calibrations was equivalent to ±1 keV at $E_{He^3} = 1.74$ MeV. To prevent energy shifts from target contamination, carbon buildup on the target surface was kept to a negligible level by the use of a liquid-nitrogen cold trap with a cold finger ~2 mm from the target. The thicknesses of the thin targets were measured in two steps: First, the thickness of a 33-μg/cm^2 Be^9 target was determined from the observed width of the narrow $Be^9(p, \gamma)B^{10}$ resonance at $E_p = 1.083$ MeV; secondly, the thicknesses of the 1.3- and 3.2-μg/cm^2 targets were obtained from a comparison of relative yields of the reaction $Be^9(d, p)Be^{10}$. The thicknesses of the latter two targets correspond to energy losses of 1.7 and 4.1 keV, respectively, for the He^3 beam at 1.74 MeV.