$T = 2$ states in ^{12}C and ^{12}B[†]

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The ^{14}C$(p,t)^{12}$C and ^{14}C$(p,{}^3\text{He})^{12}$B reactions have been investigated at $E_p = 54$ MeV. The lowest 0^+, $T = 2$ state in ^{12}C was identified at 27.57 ± 0.03 MeV and a higher $T = 2$ state was found at 29.63 ± 0.05 MeV. Their analogs in ^{12}B were found at 12.72 ± 0.07 and 14.82 ± 0.10 MeV, respectively. In a separate coincidence experiment, the proton and α decay modes of the $T = 2$ states in ^{12}C were studied. The 27.57 MeV state decays $(30 \pm 10)\%$ by proton emission and less than 10% by α emission. The 29.63 MeV state decays by about 80% proton emission and 20% α emission.

[NUCLEAR REACTIONS ^{14}C(p,t), $(p,{}^3\text{He})$, $E = 54$ MeV; measured $\sigma(\theta)$; ^{12}C, ^{12}B levels, deduced J, IAS. ^{14}C(p,tp), $(p,t\alpha)$, $E = 54$ MeV measured pt coin, $p\alpha$ coin.]

I. INTRODUCTION

In recent years there has been widespread interest in the study of $T=2$ analog states in self-conjugate nuclei, both in terms of the isospin multiplet mass equation and their isospin-forbidden decay properties.[1] Preliminary identifications of the lowest 0^+, $T=2$ states in ^{12}C have been made via the ^{14}C$(p,t)^{12}$C reaction at an excitation energy of 27.50 ± 0.10 MeV[1] and 27.595 ± 0.02 MeV.[2] In a recent study of the ^{10}Be$({}^3\text{He},n)^{12}$C reaction,[3] a peak corresponding to an excitation energy of 27.611 ± 0.02 MeV was observed at 0° and identified as the 0^+, $T=2$ state. Attempts to form this ^{12}C state as a resonance in the reactions ^{11}B$(p,\gamma\gamma)$, ^{10}B(d,p), ^{10}B(d,α), ^{10}B$(d,\gamma\gamma)$, and ^{9}Be$({}^3\text{He},\gamma\gamma)$ have also been made.[4–6] While no resonance was found in the $^{11}\text{B}+p$ or $^{10}\text{B}+d$ studies, a weak resonance was tentatively located at 27.585 ± 0.005 MeV by means of the ^{9}Be$({}^3\text{He},\gamma\gamma)$ reaction.[5] However, two reinvestigations of the $^{9}\text{Be}+{}^3\text{He}$ channel using improved techniques yielded no evidence for a resonance near this energy.[6] Thus, at present, only controversial evidence exists for the observation of the ^{12}C $(T=2)$ state as an isospin-forbidden resonance in a charged-particle system. Preliminary measurements of the 0^+, $T=2$ state in ^{12}B at 12.67 ± 0.07 MeV[1] and 12.710 ± 0.02 MeV,[2] via the ^{14}C$(p,{}^3\text{He})^{12}$B reaction, have also been reported.

II. POPULATION OF THE $T=2$ STATES

In the first part of the present work, the ^{14}C$(p,t)^{12}$C and ^{14}C$(p,{}^3\text{He})^{12}$B reactions were studied over an angular range of 14°–40° (lab) with a 54 MeV proton beam from the Lawrence Berkeley Laboratory 88-in cyclotron. The target was prepared by passing ^{14}C enriched methyl iodide through an electrical discharge system. Details of this method are described elsewhere.[7] A 450 μg/cm^2 target (largely iodine) supported on a 560 μg/cm^2 gold backing was used for this experiment; the actual ^{14}C thickness, determined from activity measurements, was about 90 μg/cm^2. Outgoing triton and ^{3}He particles were detected by a pair of detector telescopes, each with thicknesses $\Delta E = 160$ μm, $E = 3$ mm, $E_{\text{Rej}} = 0.5$ mm, coupled to standard particle identification systems.

Figure 1 shows the triton and ^{3}He spectra obtained at $\theta_{\text{lab}} = 23°$. Possible transitions to two $T=2$ states are visible in each spectrum, at excitation energies of 27.57 ± 0.03 and 29.63 ± 0.05 MeV in ^{12}C, and 12.72 ± 0.07 and 14.82 ± 0.10 MeV in ^{12}B. Figure 2 presents a portion of the high-excitation region of a triton spectrum at $\theta_{\text{lab}} = 27°$ showing the two states with very good statistics. Angular distributions for the four states are shown in Fig. 3. All the ^{3}He data points have been multiplied by the theoretically predicted[8] cross section ratio for $T_i \to T_f = T_i + 1 = 2$ analog transitions, $R = \sigma(p,t)/\sigma(p,{}^3\text{He}) = \frac{2}{3}k_t/k_{^3\text{He}} = 0.64$. There is an over-all uncertainty of about 30% in the absolute cross sections, due mainly to uncertainty in the ^{14}C enrichment of the target. The smooth curves in Fig. 3 are arbitrarily normalized "experimental" angular distributions for $L=0$ and $L=2$ transitions. They were taken from angular distributions measured in the present work for the ^{12}C$(p,t)^{10}$C reaction leading to the ground (via $L=0$) and 3.35 MeV (via $L=2$) states. As can be seen, the angular distributions of the lower states [^{12}C(27.57 MeV), ^{12}B(12.72 MeV)] are consistent with an $L=0$ transition, and the experimental cross section ratio of $R = 0.57 \pm 0.15$ agrees with

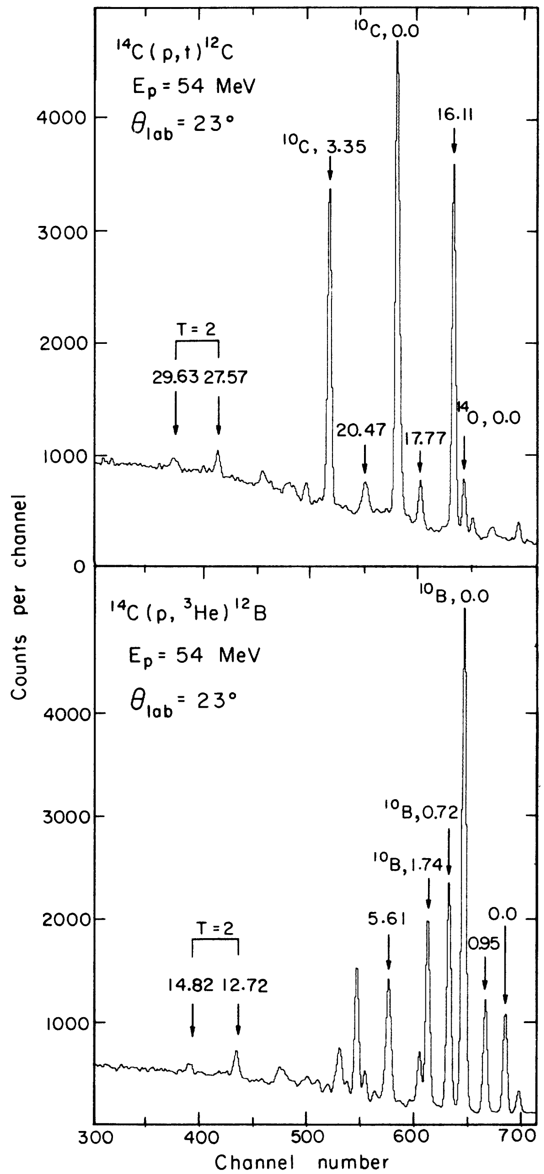

FIG. 1. Energy spectra from the $^{14}C(p,t)$ and ^{14}C-$(p,{}^3He)$ reactions at 54 MeV. Locations of the $T=2$ states are indicated. The ^{10}C and ^{10}B levels are due to the ^{12}C isotopic impurity.

the expected value $R=0.64$. Since the relative excitation energies for these states also agree with Coulomb displacement energy calculations, we can reasonably identify them as the lowest 0^+, $T=2$ levels in ^{12}C and ^{12}B. It should be pointed out here that the cross sections measured for these states (~10 μb/sr) are considerably lower than those typically found for (p,t) transitions to the lowest $T=2$ states in other light nuclei.[9]

The higher levels seen in this work, at 29.63 MeV in ^{12}C and 14.82 MeV in ^{12}B, both lie at an

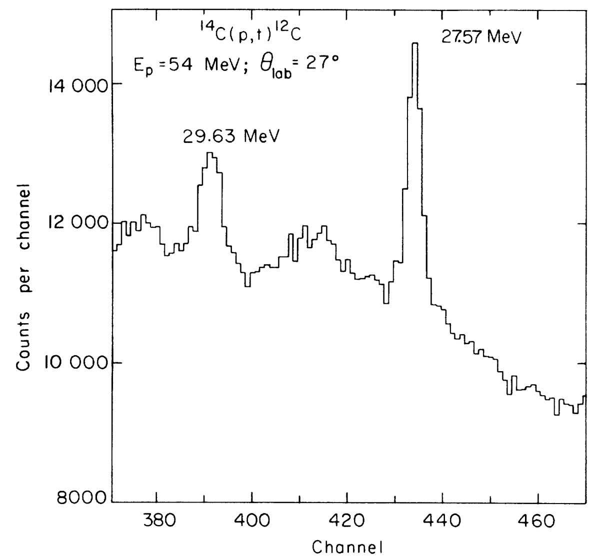

FIG. 2. High excitation energy portion of the $^{14}C(p,t)$ spectrum containing the two $T=2$ states in ^{12}C. These data were taken during the coincidence experiment discussed in Sec. III.

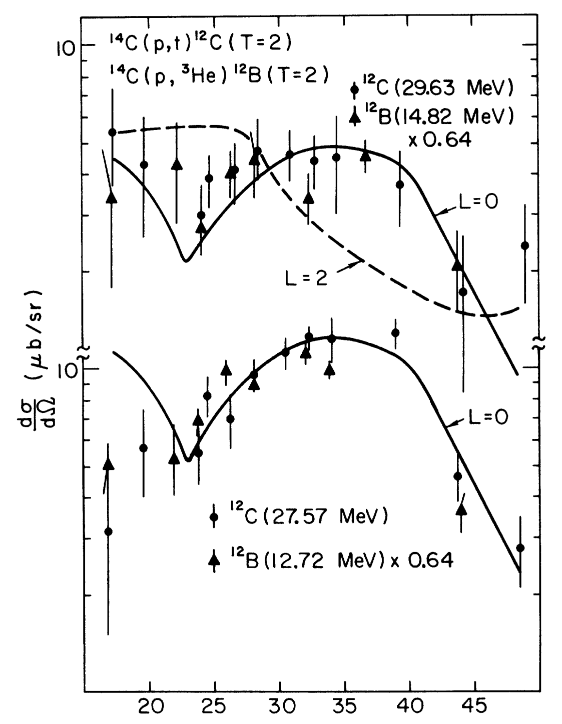

FIG. 3. Angular distributions of the $^{14}C(p,t)$ and ^{14}C-$(p,{}^3He)$ reactions leading to the $T=2$ states. The ^3He points have all been multiplied by the theoretical $(p,t)/(p,{}^3He)$ cross section ratio of 0.64. The smooth curves are "experimental" $L=0$ and $L=2$ angular distributions from the $^{12}C(p,t)$ reaction (see text).

excitation energy of about 2.1 MeV above their respective 0^+, $T=2$ levels. A ^{12}B level at this energy was also seen by Nettles[10] in the $^{14}C(p, {}^3He)$ reaction at $E_x = 14.86 \pm 0.03$ MeV, although his data did not allow him to assign its isospin. In a recent study of the $^{14}C(^{18}O, {}^{12}Be)^{20}Ne$ reaction,[11] a ^{12}Be excited state was identified at an excitation energy of 2.09 ± 0.05 MeV. This suggests the possibility that the ^{12}C(29.63 MeV) and ^{12}B(14.82 MeV) levels are also $T=2$ states, analogs of the 2.09 MeV state in ^{12}Be. [Excited $T=2$ states in other light nuclei have been observed previously in the (p, t) reaction[9] as well as in the $(^3He, n)$ reaction[12] and several resonance experiments.[13]] The experimental cross section ratio for the ^{12}C(29.63 MeV) and ^{12}B(14.82 MeV) states, $R = 0.81 \pm 0.30$, is not in disagreement with this assumption. Although the quality of the data is poor, the angular distribution shapes (see Fig. 3) appear more consistent with an $L=0$ than with an $L=2$ transition. It should be noted that the analysis of these data was hampered by low cross sections and high background; additionally, analysis of the 29.63 MeV level was made particularly difficult by the presence in this region of the spectrum of a ^{10}C impurity peak over most of the angular range. These problems make it impossible to extract reliable widths for the two upper $T=2$ states. If we use the lower $T=2$ levels (which have very small widths[10]) as a measure of the experimental resolution, the data for the upper $T=2$ levels in both final nuclei indicate a very rough upper limit for the widths of $\Gamma_{c.m.} \lesssim 200$ keV. Nettles[10] reports a width for the 14.86 MeV level seen in his $^{14}C(p, {}^3He)$ data of $\Gamma_{c.m.} = 226 \pm 30$ keV, but he could not rule out the possibility that the level was actually a doublet.

It has recently been proposed by Barker[14] that the second $T=2$ level in mass 12 is a 0^+ state rather than a 2^+. In this model, which is based on a ^{10}Be "core," both the lowest and first excited 0^+, $T=2$ levels would be composed of highly mixed configurations of $(1p^8)$, $(1p^6 2s^2)$, and $(1p^6 1d^2)$. The strong mixing results from the close proximity of the sd-shell levels to the $p_{1/2}$ level in this mass region. Evidence for the nearness of sd-shell and p-shell states is seen in ^{11}Be where the ground state is actually a $\frac{1}{2}^+$ state, followed by a $\frac{1}{2}^-$ state at 0.32 MeV and a possible $\frac{5}{2}^+$ state at 1.78 MeV.[15] This close spacing was explained by Talmi and Unna[16] as a consequence of the residual interaction between protons and neutrons depressing the energies of the $2s_{1/2}$ and $1d_{5/2}$ states. Barker's calculation[14] predicts the first excited $T=2$ state to be a 0^+ lying at about 2 MeV above the lowest 0^+, $T=2$ state, in contrast to the Cohen-Kurath p-shell calculations[17] which would give the first excited $T=2$ state as a 2^+ level (but lying considerably higher in excitation energy—about 4 MeV above the lowest 0^+, $T=2$ level).

We note that certain properties of these states appear to agree quite well with Barker's model. In particular, if the $T=2$ states possess significant sd-shell character, which cannot be reached directly in the $^{14}C(p, t)$ reaction, one would have an explanation for the low cross sections for populating them in this way. [By comparison, the $^{10}Be(^3He, n)$ reaction,[3] which can reach both p-shell and sd-shell components of the wave functions, populates the lower $T=2$ state in ^{12}C with a cross section typical of those for other transitions to 0^+, $T=2$ analog states in light nuclei.] Also, the observed level spacing of ~2.1 MeV between the ground and first excited $T=2$ states in mass 12 comes naturally from the configuration-mixed wave functions. Consideration of the decay channels open to the upper $T=2$ states gives very small predicted widths ($\Gamma_{c.m.} \lesssim 1$ keV) for 2^+ levels, but significant widths ($\Gamma_{c.m.} \sim 300$ keV) for 0^+ states[14]; the latter value is most consistent with the measured ^{12}B (14.86 MeV) width of 226 ± 30 keV.[10] However, the large width ($\Gamma_{c.m.} \sim 340$ keV) predicted[14] for an excited 0^+, $T=2$ level in ^{12}C is due mainly to isospin-*allowed* decays to $T=\frac{3}{2}$ states in ^{11}B, in disagreement with the decay data presented below. Of course, the fact that our angular distributions for the upper $T=2$ states do appear to agree somewhat better with an $L=0$ than with an $L=2$ shape also lends support to Barker's model.

III. DECAY OF THE ^{12}C $T=2$ STATES

Interest in the isospin-forbidden particle decay modes of the $T=2$ states in light nuclei stems from their relevance to the understanding of the isospin nonconserving interaction.[18] The apparent failure of attempts to observe the 0^+, $T=2$ state in ^{12}C in charged-particle resonance studies[4-6] prompted the second part of this experiment, in which the proton ($\Delta T=1$) and α ($\Delta T=2$) decay modes of the two lowest $T=2$ states of ^{12}C were investigated. Previous studies of the decay modes of 0^+, $T=2$ states in other light nuclei[18] have shown that proton and α decay account for almost all of the decay width. However, one difference between the $T=2$ states in ^{12}C and the $T=2$ states in these other nuclei is that, while the latter states are all bound with respect to (isospin-forbidden) neutron emission, the states in ^{12}C are unbound to this decay mode. The various possible decay modes of the $T=2$ states in ^{12}C are summarized in Fig. 4.

In order to populate these states, we again uti-

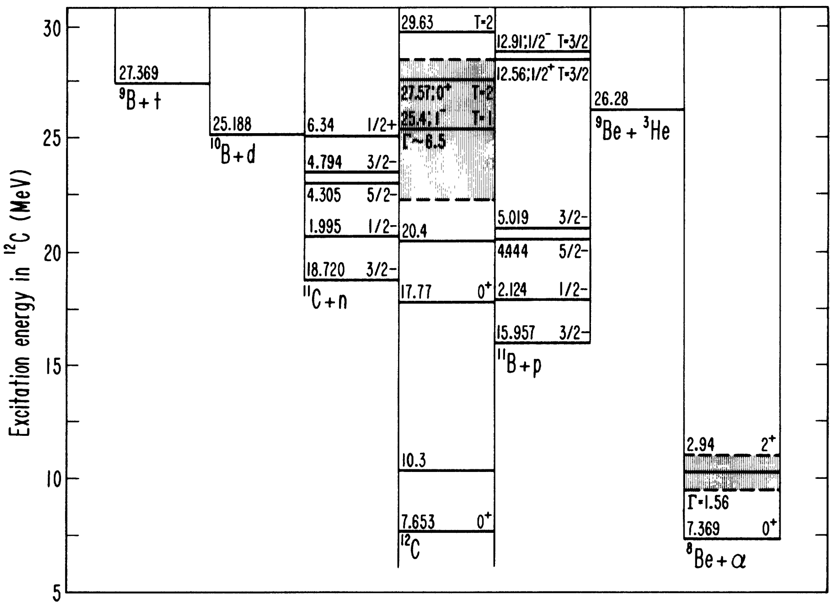

FIG. 4. Level diagram for ^{12}C and various decay channels.

lized the ^{14}C$(p,t)^{12}$C reaction at $E_p = 54$ MeV. A detector telescope consisting of $\Delta E = 220$ μm, $E = 3$ mm, $E_{\text{Rej}} = 0.5$ mm and having a solid angle of about 1 msr was set at $\theta_{\text{lab}} = 27°$ to detect the outgoing tritons. To detect the decay protons and α particles, two other detector telescopes (each with $\Delta E = 80$ μm, $E = 3$ mm, $E_{\text{Rej}} = 0.5$ mm and having a solid angle of about 14 msr) were placed at 85° and 120° in the same plane, on the opposite side of the beam axis. All three telescopes were coupled to particle identification systems and a coincidence (70 ns resolving time) was required between the triton telescope and either of the two decay telescopes. Dead-time restrictions led to a maximum singles count rate of about 50 kHz in the recoil counters at a beam intensity of about 400 nA on target. For each coincidence event the triton energy, the decay particle energy, and its particle identification signal were recorded on magnetic tape, together with the associated signal from the time-to-amplitude converter which was used to determine the fast coincidence between the triton and the decay telescopes. The singles triton spectrum was recorded separately and dead-time corrections were made for both the singles and coincidence data. The very low cross sections for the $T = 2$ states in ^{12}C (~11 μb/sr for the 27.57 MeV state, ~4 μb/sr for the 29.63 MeV state)—almost an order of magnitude smaller than those found in heavier $T_z = 0$ nuclei—makes this experiment particularly difficult. The measurement was carried out for a total of 54 000 μC, and only a total of 30 coincidence events from the decay of the 27.57 MeV 0$^+$, $T = 2$ state could be expected in the two decay telescopes.

The coincidence triton-proton spectrum obtained with the decay telescope at 85° is shown in Fig. 5. Kinematic lines corresponding to proton decay to the ground and first three excited states of ^{11}B are indicated. As can be seen, the kinematic line

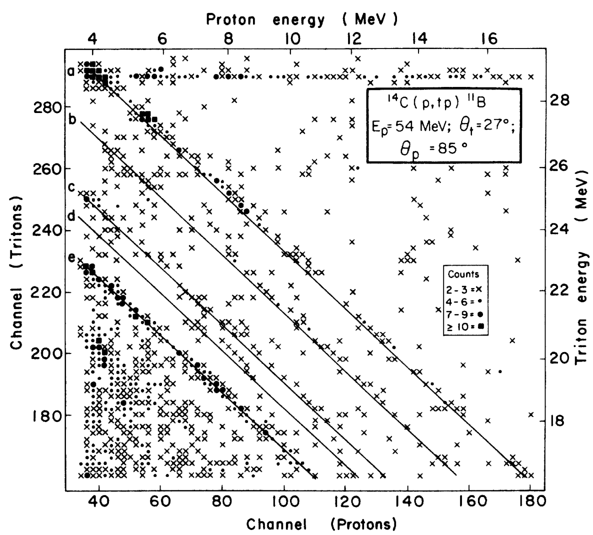

FIG. 5. Triton-proton coincidence spectrum at $\theta_{\text{lab}}^{\text{decay}} = 85°$. Kinematic lines are shown for proton decay of ^{12}C leading to (a) ^{11}B (g.s.), $\frac{3}{2}^-$; (b) ^{11}B (2.12 MeV), $\frac{1}{2}^-$; (c) ^{11}B (4.44 MeV), $\frac{5}{2}^-$; (d) ^{11}B (5.02 MeV), $\frac{3}{2}^-$. Kinematic line (e) corresponds to the ^{12}C$(p,tp)^9$B (g.s.) reaction from the isotopic impurity in the target.

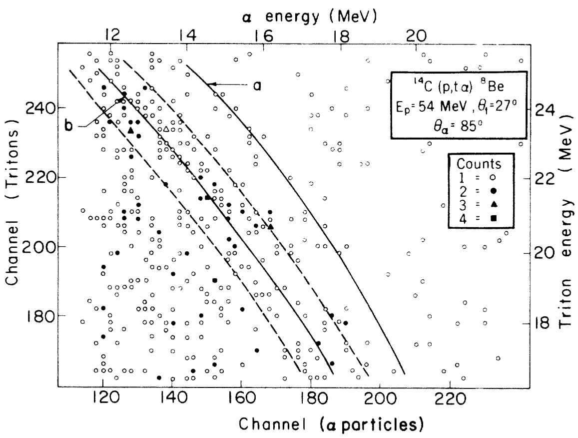

FIG. 6. Triton-α coincidence spectrum at $\theta_{\rm lab}^{\rm decay} = 85°$. Kinematic lines are shown for α decay of ^{12}C leading to (a) ^{8}Be (g.s.), 0^+; (b) ^{8}Be (2.94 MeV), 2^+. The dashed lines indicate the width of the ^{8}Be excited state.

for proton decay to the ^{9}B ground state due to the ^{12}C$(p, tp)^{9}$B reaction is well separated from the other kinematic lines. The counts found outside the kinematic lines are due to random coincidence events. Apart from the strong random line at triton channel 290 (due to the strongly populated ^{10}C ground state), the number of randoms is small and introduces a very minor correction in the analysis. Data obtained with the other decay telescope were quite similar.

Figure 6 shows the coincidence triton-α spectrum obtained with the decay telescope at 85°. In general the yield is smaller than in the proton spectra and the ^{12}C target impurity does not contribute here. The kinematic line corresponding to decay to the ^{8}Be ground state and a kinematic band corresponding to decay to its broad first excited state are indicated; most of the observed events appear along the broad excited state kinematic band.

Each triton-proton and triton-α kinematic line was projected onto the triton energy axis. In order to obtain the branching ratios for the decay to individual final states, the peaks corresponding to the $T = 2$ states in each projection must be integrated and a smooth background removed. However, the low yield of this coincidence experiment caused by the small cross sections for populating the $T = 2$ states, and the fact that the decay of these states—especially the lower one—is fragmented among the various final states made it difficult to extract reliable branching ratios. In Figs. 7(a) and 7(b) the sum of the projections of the kinematic lines corresponding to proton decay to the four observed ^{11}B final states is presented for each decay telescope. Also shown [Fig. 7(c)] is the sum of these two spectra. Two weak peaks, corresponding to the decay of the 27.57 and 29.63 MeV states, are observed in these projections. Decays from the 27.57 MeV 0^+, $T = 2$ state are observed with comparable intensity at the two angles, consistent with the expected iso-

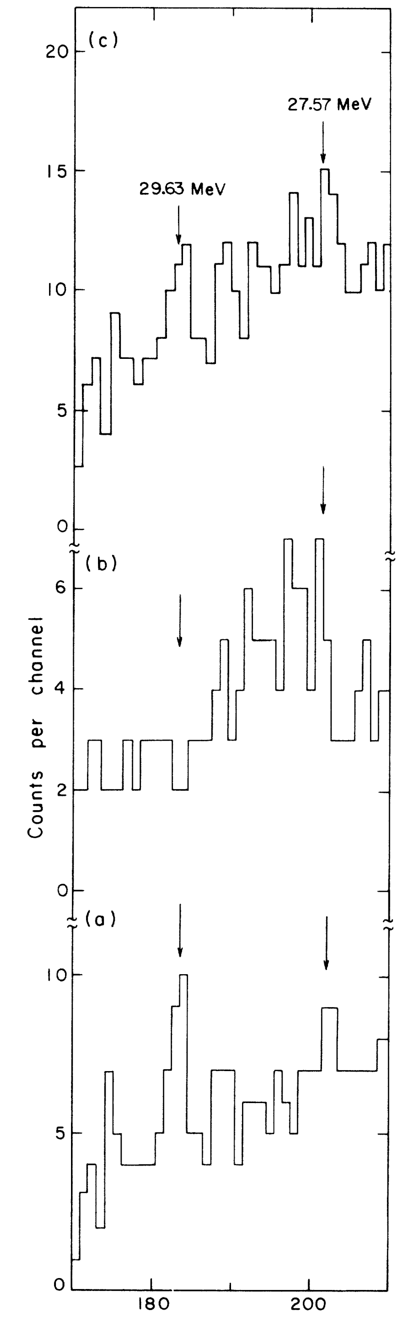

FIG. 7. Sum of projections on the triton energy axis of the four ^{11}B kinematic lines (a) $\theta_{\rm lab}^{\rm decay} = 85°$; (b) $\theta_{\rm lab}^{\rm decay} = 120°$; (c) sum of (a) and (b).

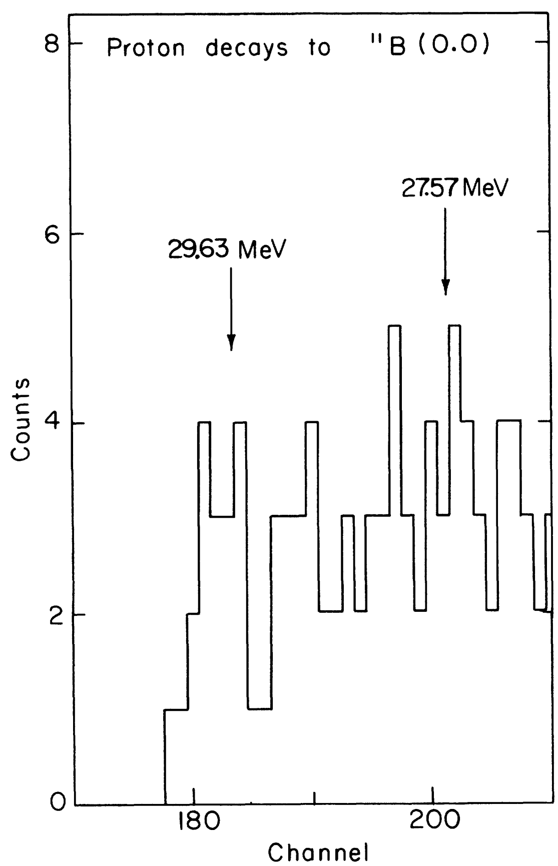

FIG. 8. Projection on the triton energy axis of the ^{11}B (g.s.) kinematic line, summed over the two decay angles.

tropic angular distribution. The angular distribution for the decay of the 29.63 MeV state, however, does not appear isotropic since the intensity of its decay peak at $\theta_{lab} = 120°$ is weaker than that at 85°. This result, which is at variance with the tentative $L = 0$ assignment favored by the angular distribution data, will be discussed below.

Integration of the 0^+ $T = 2$ peak at 27.57 MeV yields $(\sum_{i=0}^{3}\Gamma_{p_i})/\Gamma \equiv \Gamma_p/\Gamma = 0.3 \pm 0.1$, where Γ_{p_i} is the partial proton decay width to the ith state in ^{11}B. The α decay of the 27.57 MeV state, obtained from projection of the triton-α coincidence spectra, is very weak and only an upper limit for decay to the ^{8}Be 2.9 MeV state of $\Gamma_{\alpha_1}/\Gamma < 0.1$ can be set. The α decay of the 27.57 MeV state to the ^{8}Be ground state did not yield statistically significant results. All the branching ratios were obtained using a dead-time correction measured during the experiment. Since there is a possibility that this correction may have been too large, the real branching ratios could be systematically smaller by as much as 25%.

Of particular interest is the decay branch leading to the ^{11}B ground state. The projection of this kinematic line (summed over the two decay telescopes) is shown in Fig. 8. Although very weak, it seems that there is some proton decay to this state, with a branching ratio $\Gamma_{p_0}/\Gamma \lesssim 0.1$. A study of the ^{11}B$(p,\gamma\gamma)^{12}$C reaction,[4] in which an attempt was made to form the 0^+, $T = 2$ state as a resonance, set an upper limit $\Gamma_{p_0}/\Gamma < 0.03$ by assuming 1 Weisskopf unit (W.u.) for the γ-decay strength. Considering the possibility of a smaller γ decay width (for example, Barker's estimate,[19] based on configuration-mixed wave functions, of 0.3 W.u.) and the uncertainty in our present measurement, these results are not inconsistent.

In view of the fact that only 30–40% of the decay strength of the 27.57 MeV 0^+, $T = 2$ level has been observed in the present experiment, other decay channels must account for a substantial fraction of the decay width. With all of the open, though isospin-forbidden, heavy particle decay channels available for this state, γ decay is not expected to account for a substantial share of the total width. [The isospin-allowed decay to ^{10}Be + 2p, which is only open by about 400 keV, is expected[19] to have a partial width of ≈0.1 eV.] Based on Barker's calculations,[19] a reasonable estimate for the neutron width might be that it is about the same as that observed for protons, i.e., $\Gamma_n/\Gamma \approx 0.3–0.4$. If this were the case, there would still be some fraction (~20 to 40%) of the decay strength which is unaccounted for. Prediction of the isospin-forbidden decay properties, of course, depends greatly on which levels are assumed to mix strongly with the 0^+, $T = 2$ level. Barker's calculations[19] suggest the possibility that the deuteron channels d_0 and d_1 may carry the "missing" decay strength. At present these exit channels have not been investigated experimentally.

Determination of the decay modes of the upper $T = 2$ state was based on averaging over the two angles at which data were taken. With this assumption we obtain $(\sum_{i=0}^{3}\Gamma_{p_i})/\Gamma = 0.8 \pm 0.2$ and $\Gamma_{\alpha_1}/\Gamma \approx 0.2$. Thus, in contrast to the case of the 27.57 MeV state, it appears that the charged-particle decay modes observed for the 29.63 MeV state account for most of its decay width. Furthermore, analysis of the projections of the individual kinematic lines indicates that this state decays mainly to the ^{11}B ground state, with some strength to the second-excited state of ^{11}B ($\frac{5}{2}^-$, 4.44 MeV). Our data yield $\Gamma_{p_0}/\Gamma \approx 0.4$, which is large enough to suggest a reasonable prospect for observing this state as a resonance in the ^{11}B + p system. Such a resonance experiment would very probably permit a determination of whether or not the upper $T=2$ level is in fact a single state. We reiterate that, although the width of the 29.63 MeV state is in reasonable agreement with Barker's estimate[14] for a 0^+ level, its decay scheme is not. The large width predicted for a 0^+, $T=2$ state comes mainly from isospin-*allowed* decay to the $\frac{1}{2}^+$, $T=\frac{3}{2}$ level at 12.56 MeV in ^{11}B, while we find essentially all of the decay strength going into isospin-forbidden transitions. This objection applies equally to a 2^+ assignment if configuration mixing is included, since the decay of this 2^+ state is then also expected[14] to occur primarily to the $\frac{1}{2}^+$, $T=\frac{3}{2}$ state in ^{11}B. (How the decay data affect a J^π assignment for this state is discussed additionally below.)

IV. SUMMARY

The lowest 0^+, $T=2$ states in ^{12}C and ^{12}B, at excitation energies of 27.57 ± 0.03 and 12.72 ± 0.07 MeV, respectively, have been populated by means of the $^{14}C(p,t)$ and $^{14}C(p,{}^3He)$ reactions at 54 MeV. The angular distributions and (p,t) to $(p,{}^3He)$ cross section ratio for these levels are consistent with those expected for population of 0^+, $T=2$ analog states, but the magnitudes of the cross sections are much smaller than those found for other such states in light nuclei. A second pair of levels [^{12}C (29.63 ± 0.05 MeV), ^{12}B(14.82 $\pm$ 0.10 MeV)] has also been observed with roughly the cross section ratio expected for $T=2$ analog levels and relative excitation energies (~2.1 MeV) in agreement with that found for an excited state of ^{12}Be. The angular distributions for these excited $T=2$ levels appear somewhat more consistent with an $L=0$ than with an $L=2$ shape, although the possibility of a doublet cannot be excluded. A 0^+ assignment for these excited $T=2$ states would be in agreement with recent theoretical calculations of Barker,[14] which are based on configuration mixing with *sd*-shell components.

Coincidence data on the proton and α decay of the two levels in ^{12}C were also obtained in a separate experiment. For the lower state (27.57 MeV) we find $\Gamma_p/\Gamma \approx 0.3 \pm 0.1$ and $\Gamma_{\alpha_1} < 0.1$. Assuming roughly equal neutron and proton widths, there is some "missing" decay strength which might be found[19] in the deuteron exit channels d_0 and d_1. It would, therefore, be very interesting to look for this state as a resonance via the $^{11}B(p, d_0/d_1)$ or $^{10}B(d, d_0/d_1)$ reactions. For the upper state (29.63 MeV) we find $\Gamma_p/\Gamma = 0.8 \pm 0.2$ and $\Gamma_\alpha/\Gamma \approx 0.2$. The branching ratio to the ^{11}B (g.s.) for this state, $\Gamma_{p_0}/\Gamma \approx 0.4$, is large enough to offer a reasonable possibility for observing it as a resonance in $^{11}B + p$. The apparent anisotropy of the decay data and the existence of a decay branch to the $\frac{5}{2}^-$, 4.44 MeV level in ^{11}B both argue against $J^\pi = 0^+$ for the upper $T=2$ state. However, because of the poor quality of the decay data, it is not clear that these results invalidate the dominant character of the angular distribution measurement. Further experiments on this $T=2$ state and its decay appear to be necessary.

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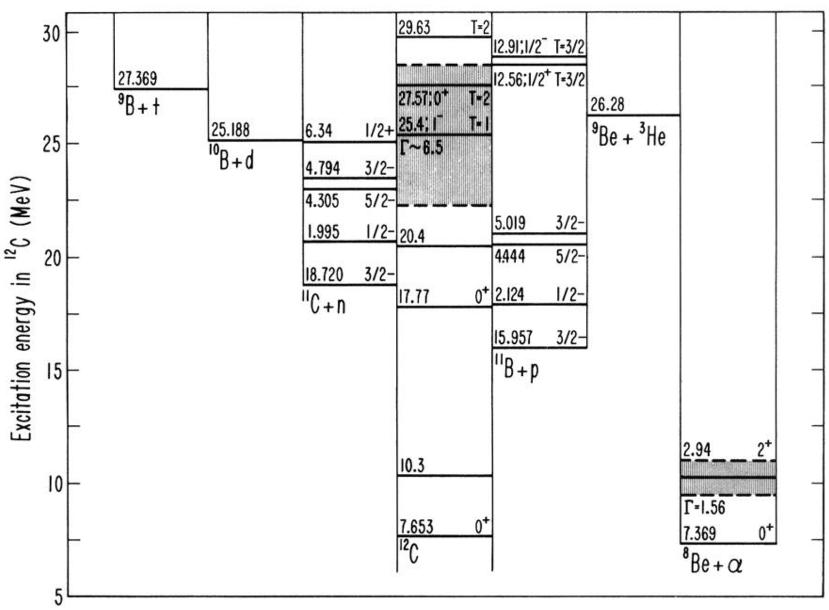

FIG. 4. Level diagram for ^{12}C and various decay channels.