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He^3 Reactions on B^{11} and N^{14}

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The $5/2^-$ level expected in the mass-13 nuclei according to shell-model calculations has been searched for by magnetic analysis of the $B^{11}(He^3,p)C^{13}$ and $N^{14}(He^3,\alpha)N^{13}$ reactions using a broad-range magnetic spectrograph. Up to an excitation energy of 7.9 MeV in C^{13} and 7.0 MeV in N^{13}, no new levels have been found. C^{13} states reported previously at 5.51 and 6.10 MeV in the $B^{11}(He^3,p)C^{13}$ reaction have not been confirmed. The apparent absence of a $5/2^-$ state up to ≈ 7 MeV excitation suggests that the intermediate coupling parameter a/K may be smaller than presupposed. In an investigation of the $B^{11}(He^3,\alpha)B^{10}$ reaction we have resolved the 5.11–5.16-MeV doublet. B^{10} levels reported previously at 2.86, 5.58, and 6.40 MeV have not been confirmed by studies of this reaction.

INTRODUCTION

ENERGY levels in the mirror nuclei C^{13} and N^{13} have been the subject of considerable experimental investigation and theoretical analysis. The nuclei[1] have a ground state of $J^\pi = 1/2^-$. The first three C^{13} excited states, at 3.09, 3.68, and 3.85 MeV of spin-parity $1/2^+$, $3/2^-$, and $5/2^+$, respectively, are matched by N^{13} states at 2.365, 3.51, and 3.56 MeV with the same spin-parity sequence. After a large energy gap the next level in N^{13} is the $5/2^+$ state at 6.38 MeV which presumably corresponds to the $5/2^+$ state at 6.86 MeV in C^{13}. However, in C^{13} two additional levels at 5.51 and 6.10 MeV have been reported by Moak *et al.*[2] They used the $B^{11}(He^3,p)$-C^{13} reaction at $E_{He^3} = 1.2$ MeV and detected proton groups in a scintillation crystal.

Apart from the difference in the number of levels reported in C^{13} and N^{13} up to the second $5/2^+$ state, a major difficulty in understanding the $A = 13$ system lies in the apparent absence of the low-lying $5/2^-$ state expected from shell-model calculations. An early and outstanding success of the shell model in light nuclei was the treatment of the $A = 13$ nuclei by Lane,[3] who showed that the position of the first excited odd-parity state ($3/2^-$), the magnetic moment of C^{13}, the beta decay of N^{13}, the reduced width of the $3/2^-$ state and the $M1$ transition of the 3/2 state to ground could simultaneously receive a good account for a value of the intermediate coupling parameter in the close neighborhood of $a/K = 5$. Since that time this has been the chief anchoring point for our ideas about the values of a/K in the $1p$ shell. It was clear from the calculations of Kurath,[4] however, that this value of a/K requires a $5/2^-$ state at an excitation of about 5 MeV. This prediction is not very sensitive to the force mixture used. Figure 1 shows the predicted excitation for the Kurath[4] and Soper[5] force mixtures (the energy scale is established by the excitation of the $3/2^-$ state). It has not proved possible, for reasonable assumptions about the effective residual nucleon-nucleon interaction, to understand the nonappearance of a low-lying $5/2^-$ state for values of a/K in the neighborhood of 5. As is seen from Fig. 1, to remove the $5/2^-$ state to an excitation of about 7.5 MeV, where well-established nonassigned states are found and so which may contain the state in question, we should have to take $a/K \approx 3$ or less. (We may note that states in C^{13} above 4.95 MeV and in N^{13} above 1.94 MeV are unstable against nucleon emission and so are liable to a Thomas shift; this makes the situation even worse). This solution of $a/K \approx 3$ conflicts sharply with the long-established description of $A = 13$.

While one of the two new states in C^{13} found by Moak *et al.*[2] might have corresponded to the missing level there has been no evidence for a matching level in N^{13}. Furthermore there has been doubt as to the existence of the C^{13} levels at 5.51 and 6.10 MeV. In a

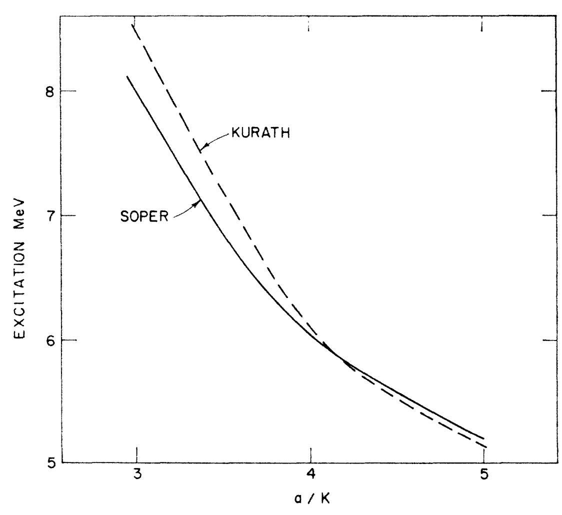

FIG. 1. Theoretical excitation energy of the $5/2^-$ state in $A = 13$ nuclei as a function of a/K for the Kurath and the Soper force mixtures.

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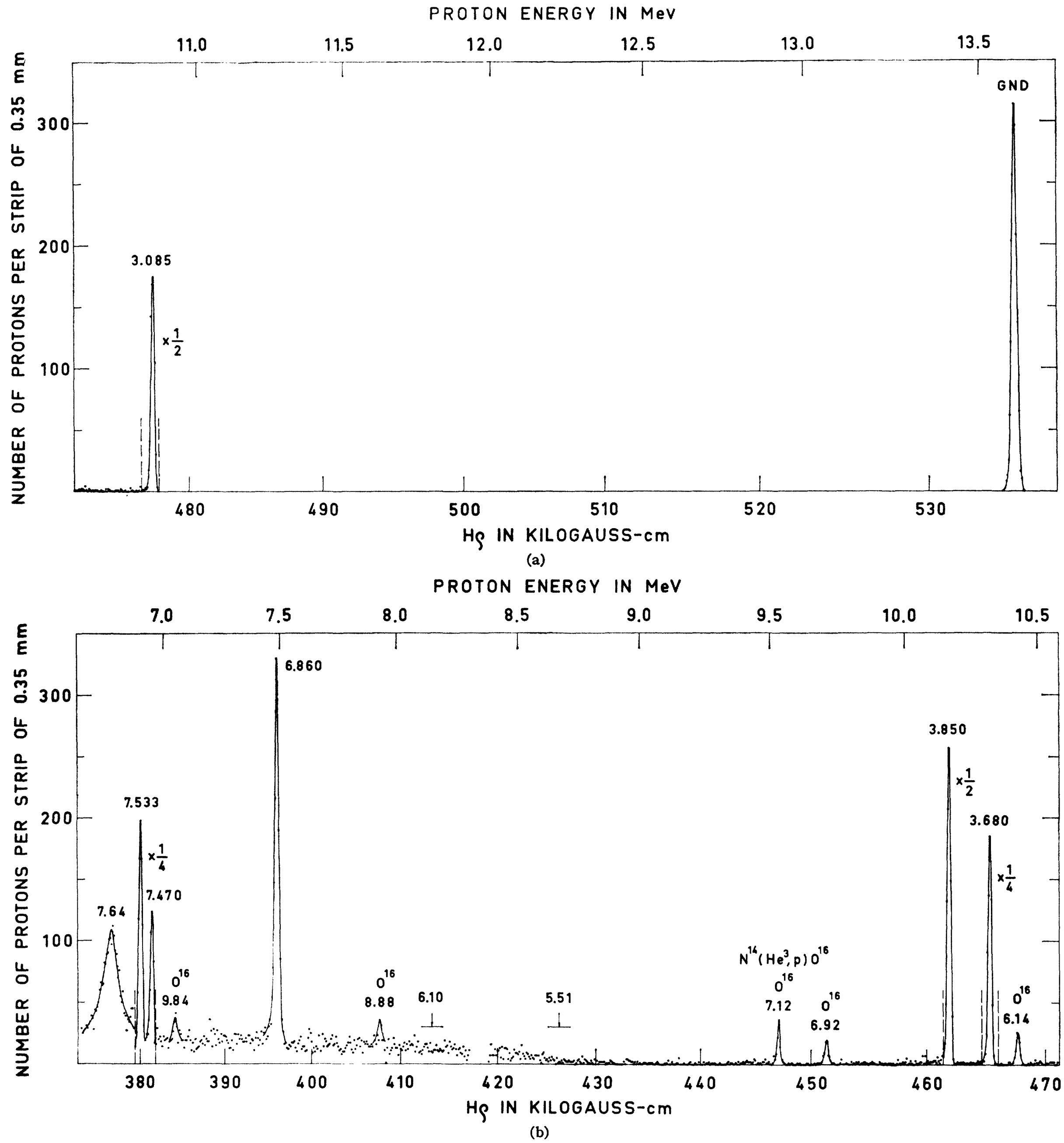

FIG. 2. Proton spectrum from the $B^{11}(He^3,p)C^{13}$ reaction at $E_{He^3}=3.50$ MeV and $\theta=132.5°$.

magnetic analysis of protons from the $B^{11}(He^3,p)C^{13}$ reaction, Young *et al.*[6] did not observe groups corresponding to these two levels. However, because of the small total yield of their spectrum their upper limits for the relative intensities of the 5.51- and 6.10-MeV groups were comparable to the actual intensities reported by Moak *et al.*[2] These levels had not been seen by magnetic analysis of proton groups in the $C^{12}(d,p)C^{13}$ reaction by Green and Middleton.[7] In a more recent specific search for these two states, Gorodetzky *et al.*[8] did not find the corresponding proton groups in the $C^{12}(d,p)C^{13}$ reaction. Either the proton groups were too weak to observe in this reaction or the peaks found by Moak *et al.*[2] did not actually arise from the $B^{11}(He^3,p)C^{13}$ reaction.

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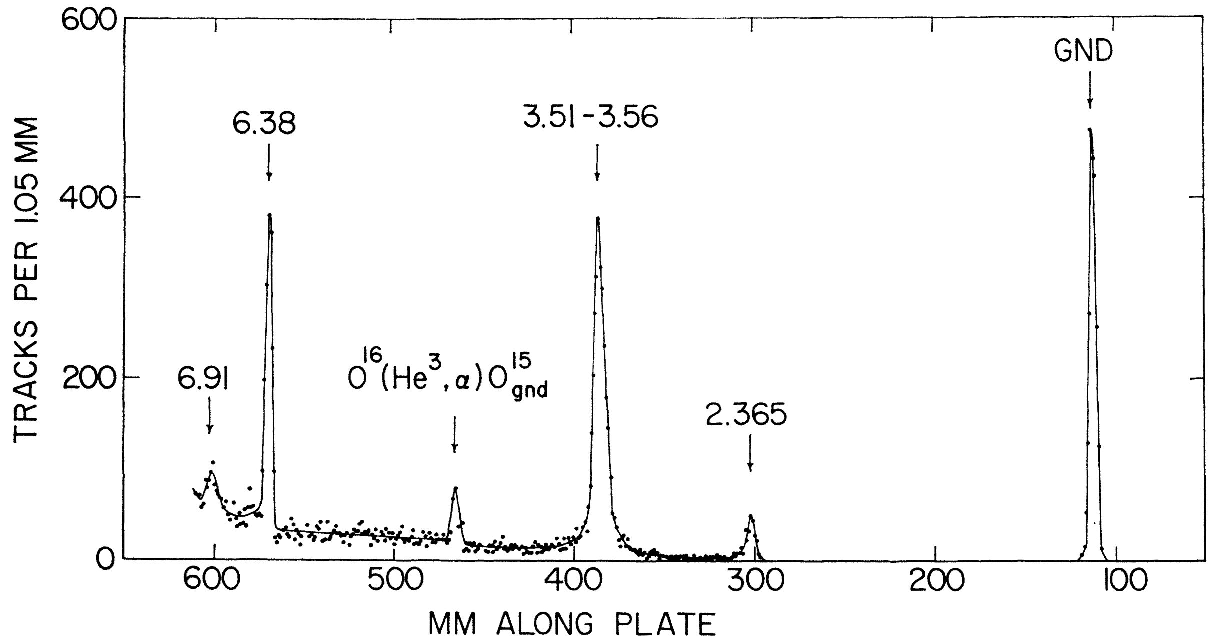

FIG. 3. Alpha-particle spectrum from the $N^{14}(He^3,\alpha)N^{13}$ reaction at $E_{He^3}=4.59$ MeV and $\theta=90°$.

Since the absence of the $5/2^-$ state is difficult to understand, we must conclude either that the level is too weakly populated to have been observed in any of the reactions used thus far (which seems improbable) or that the standard value of $a/K\approx5$ must be challenged. Other data now indeed point to a lower value for a/K. Since the earlier analysis[3] was made, the magnetic moment of N^{13} has been measured.[9] This is not well described by $a/K\approx5$. Indeed, it is not possible to bring into consistency within the shell-model calculation for any value of a/K, the three pieces of data that depend on $\sigma\tau$, namely the C^{13} and N^{13} magnetic moments together with the Gamow-Teller part of the N^{13} beta decay, if it is assumed that the effective Gamow-Teller coupling constant in complex nuclei for shell-model calculations is that derived from the decay of the free neutron. There is strong empirical evidence,[10] however, that if simple independent-particle model (IPM) wave functions are used for calculations of beta decay, one should reduce the effective Gamow-Teller term by about 15% below that derived directly from the neutron-decay rate. The bulk of this correction is probably associated with the imperfections of the simple IPM wave functions. (This empirical correction is arrived at by assuming that the Fermi part of the beta decay is given exactly through the conserved vector current hypothesis.) If this correction is applied to the N^{13} decay, that decay and the two magnetic moments are simultaneously accurately fit for a value of a/K of a little below 3.[5] The account given of the other data is still acceptable. If the absence of a $5/2^-$ state below 7 MeV is confirmed, we therefore have a rather powerful argument that the effective value of a/K must be considerably less than presupposed.

We have investigated the $B^{11}(He^3,p)C^{13}$ and $N^{14}(He^3,\alpha)N^{13}$ reactions, not only to search for the "missing" $5/2^-$ level in both of the $A=13$ nuclei, but to check on the existence of the 5.51- and 6.10-MeV levels in C^{13} which had been found by Moak *et al.*[2] in the B^{11} plus He^3 reaction.

At the time these experiments were performed, there was conflicting evidence on the assignment of a $J^\pi=2^+$, $T=1$ level in B^{10} which would be the analog of the 3.37-MeV first excited state of Be^{10}. The 5.16-MeV member of the 5.11–5.16-MeV doublet appeared to be the most likely candidate for this $T=1$ state, although the apparent gamma-ray decay of the 7.56-MeV level to the 5.16-MeV state conflicted with that assignment. The situation has now been cleared up by experiments of Sprenkel *et al.*[11] who discovered a new broad state in B^{10} at 5.18 MeV. It is presumably the 5.18-MeV state to which the 7.56-MeV level decays by gamma-ray emission. Confirmation of the $T=1$ assignment to the sharp 5.16-MeV level has been obtained in proton and deuteron inelastic-scattering experiments by Armitage and Meads.[12] Our work was undertaken originally to investigate the 5.11–5.16-MeV doublet as excited in the $B^{11}(He^3,\alpha)B^{10}$ reaction, with the hope that a knowledge of level population intensities and angular distri-

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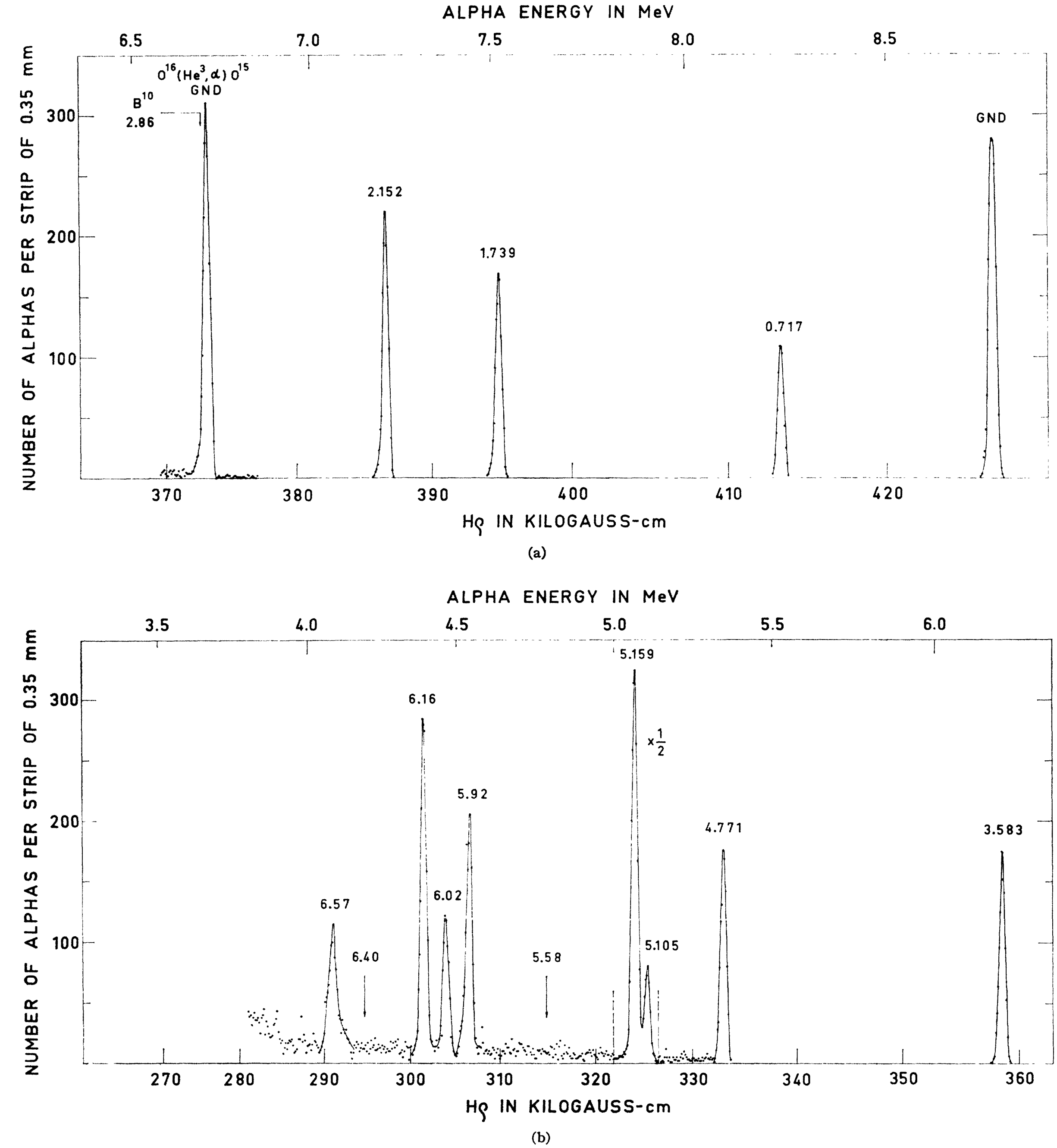

FIG. 4. Alpha-particle spectrum from the $B^{11}(He^3,\alpha)B^{10}$ reaction at $E_{He^3}=4.59$ MeV and $\theta=90°$.

butions of the alpha-particle groups might help to fix the assignment of the $T=1$ state. We present here our results on this doublet as well as on searches for certain other B^{10} levels, which have been reported in the literature. In particular we investigated a level at 2.86 MeV that had been seen by some but not by others[1] in the $Be^9(d,n)B^{10}$ neutron spectrum. Further evidence for this level based on observation of gamma-ray spectra from the same reaction has been given by Galloway and Sillitto.[13] Two other doubtful levels in B^{10} are those reported[1] at 5.58 and at 6.40 MeV.

EXPERIMENTAL METHODS AND RESULTS

In all of our work, we used a He^3 beam from the Center of Nuclear Research 5.5-MeV Van de Graaff accelerator together with a Buechner-type 40-cm radius

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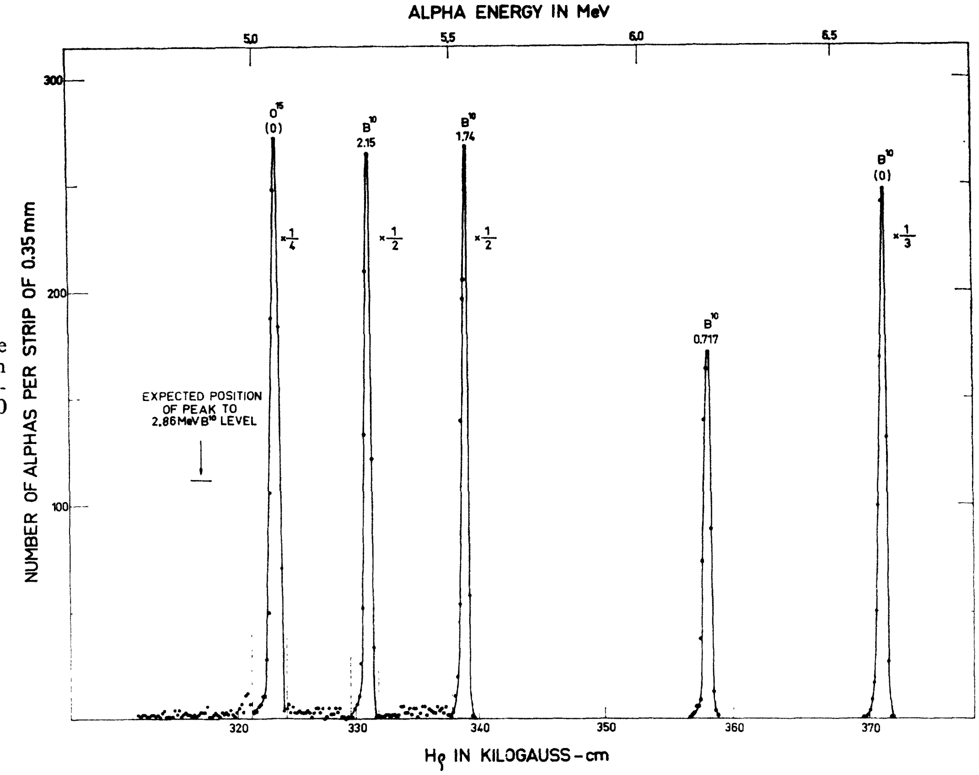

FIG. 5. A portion of the alpha-particle spectrum from the $B^{11}(He^3,\alpha)B^{10}$ reaction taken at $E_{He^3}=3.50$ MeV and $\theta=132.5°$.

broad-range magnetic spectrograph. Magnetic resonance probes were available in the beam-analyzing magnet and in the spectrograph in order to determine the beam energy and the spectrograph field strength.

The B^{11} target material was kindly prepared for us by D. J. Pullen of Oxford University. It consisted of an 8-μg/cm²-thick layer of boron evaporated onto a thick nickel foil. The nitrogen targets were made by evaporating adenine $\approx 10\ \mu$g/cm² thick onto a thick tantalum backing.

$B^{11}(He^3,p)C^{13}$

Figure 2 shows the proton spectrum observed from the $B^{11}(He^3,p)C^{13}$ reaction at 132.5° to the beam. This was a 34-hour run using a 3.50-MeV He^3 beam current of 0.012 μA. The protons were detected in Kodak NTA 50 μ emulsions. Peaks corresponding to the ground state and to the well-established levels in C^{13} at 3.09, 3.68, 3.85, 6.86, 7.47, 7.53, and 7.64 MeV are present. In addition, we see a number of weak lines all of which can be attributed to known energy levels of O^{16} excited by the $N^{14}(He^3,p)O^{16}$ reaction. A comparison of spectra taken with targets cut from the same material but separated in time by several months showed an increase with time of the relative intensities of the contamination peaks—thus indicating a build-up of nitrogen on the target.

As may be seen at the positions indicated in Fig. 2, there is no evidence for the 5.51- and 6.10-MeV levels reported by Moak *et al.*[2] Careful scanning of the entire region from the 3.085-MeV level to just above the level at 7.64 MeV did not reveal the presence of any lines corresponding to new energy levels in C^{13}.

In order to be sure of the assignments of the O^{16} peaks and to make certain that no C^{13} lines lay under the contamination peaks, we also recorded the spectra of protons emitted at 45°, 90°, and 110° to the beam, using the same beam energy and targets. A variation in the relative intensities of the contamination lines was noted, as well as a broadening of the peaks at $\theta=45°$, but all of the O^{16} line assignments were confirmed by their energy shifts relative to the C^{13} lines. These runs were comparable in quality to that shown in Fig. 2, and, although the spectra were scanned thoroughly, no evidence was found for the 5.51- and 6.10°-MeV states or for any new states up to an excitation energy of 7.9 MeV.

$N^{14}(He^3,\alpha)N^{13}$

The reaction $N^{14}(He^3,\alpha)N^{13}$ was studied both at $\theta=90°$ and at $\theta=132.5°$ using a He^3 beam energy of 4.59 MeV. Figure 3 shows the results of an 11-h run at a beam current of $\approx 0.02\ \mu$A and $\theta=90°$. Peaks are observed corresponding to the ground state and to the known levels of N^{13} at 2.365, 3.51–3.56 (unresolved), 6.38, and 6.91 MeV. The assignment of the peak labeled $O^{16}(He^3,\alpha)O_{g.s.}$[15] was confirmed by its relative shift between the two angles of observation. Careful scanning of both runs failed to reveal peaks corresponding to new levels in N^{13} up to an excitation energy of 7 MeV.

$B^{11}(He^3,\alpha)B^{10}$

The alpha-particle spectrum from the $B^{11}(He^3,\alpha)B^{10}$ reaction at $\theta=90°$ observation is shown in Fig. 4. A 4.59-MeV He^3 beam at a current of 0.10 μA was used and the length of the run was 9 h. Alpha-particle groups are observed corresponding to the ground state and to the well-established[1] states of B^{10} at 0.717, 1.74, 2.15, 3.58, 4.77, 5.11, 5.16, 5.92, 6.02, 6.16, and 6.57 MeV. The 5.11–5.16-MeV doublet is almost completely resolved, and we find that the 5.16-MeV peak is more than twice as strong as any other line in the spectrum. There is no evidence for peaks corresponding to the previously reported[1] levels at 5.58 MeV and at 6.40 MeV. In this spectrum a strong $O^{16}(He^3,\alpha)O^{15}$ ground-state, alpha-particle line falls close to the position where a possible peak corresponding to a B^{10} state of 2.86 MeV might occur.

More sensitive searches for the 2.86-MeV level were carried out by scanning alpha particles on plates originally used for studies of the $B^{11}(He^3,p)C^{13}$ reaction. Figure 5 shows the alpha-particle spectrum obtained in one of the runs at $E_{He^3}=3.50$ MeV and $\theta=132.5°$. Under these conditions, the expected position of the 2.86-MeV line is well separated from the O^{15} ground-state alpha-particle group. As may be seen from the data there is no evidence for a level in B^{10} at 2.86 MeV. Comparable results were obtained from a run at $\theta=90°$ and $E_{He^3}=3.50$ MeV.

DISCUSSION

In our work on the $B^{11}(He^3,p)C^{13}$ reaction, we have found peaks corresponding to only the well-established energy levels in C^{13} up to an excitation energy of 7.9 MeV. Between 3 and 5 MeV excitation an upper limit of 1% is placed on the intensities of any new peaks, relative to the 3.86-MeV line, and, between 5 and 7.9 MeV excitation, the upper limit is $\approx 2\%$ of the 3.86-MeV line, unless such a line is very close to one of the main peaks. In the work of Moak *et al.*[2] the proton groups to the 5.51- and 6.10-MeV levels appeared to be ≈ 5–10% as strong as the 3.86-MeV line for $E_{He^3}=1.25$ MeV and for observation at angles of 13 and 135°. Since it would be reasonable to expect these same lines to appear at our higher bombarding energy, we feel that the peaks found by Moak *et al.*[2] were probably spurious.

Our search for a possible $5/2^-$ level in N^{13} was not as sensitive as in C^{13} because of the relatively large alpha-particle background. Between excitation energies of 3.5 and 7 MeV, an upper limit of $\approx 4\%$ relative to the ground-state alpha-particle group is placed on the presence of any possible new group.

In the $B^{11}(He^3,\alpha)B^{10}$ reaction, the population of a level at 2.86 MeV in B^{10} must be less than 1% of α_0. Upper limits of $\approx 5\%$ relative to α_0 are placed on possible peaks corresponding to levels in B^{10} at 5.58 and 6.40 MeV.

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