Energy Levels of Be^9, C^{12}, and C^{13}†

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The reactions $Li^7(He^3,p)Be^9$, $B^{10}(He^3,p)C^{12}$, and $B^{11}(He^3,p)C^{13}$ have been used to study the level structures of Be^9, C^{12}, and C^{13}, respectively. Levels of Be^9 were observed at 1.83, 2.43, 3.1, and 4.8 Mev. Observations of the group corresponding to 1.83 Mev at different angles are consistent with the assumption of a level in Be^9 although a 3-body spectrum from $He^3+Li^7 \rightarrow Be^8+n+p$ could also fit the data. With the groups corresponding to the well-known C^{12} levels at 4.43, 7.65, 9.61, and 16.10 Mev used as calibrations, other levels were observed at 10.90, 11.84, 12.69, 13.30, 14.05, 14.97, 15.62, and 16.57 Mev. For the 7.65-Mev level $\Gamma_\gamma/\Gamma_\alpha < 1.4\%$ if the level emits a single γ ray of 7.65 Mev, and $\Gamma_\gamma/\Gamma_\alpha < 0.9\%$ if there is a cascade through the 4.43-Mev state as it would if it were a 0^+ level. A proton group due to an α-particle level, predicted to lie at 5.53 Mev in C^{12}, was not found and must be more than 4000 times weaker than the proton group leading to the 4.43-Mev level. Rough estimates of $\Gamma_\gamma/\Gamma_\alpha$ for the 14.97- and 12.69-Mev levels are $50\pm25\%$ and $3\pm1\%$, respectively. With the well-known C^{13} levels up to 6.87 Mev being used as calibrations, other levels were observed at 5.51, 6.10, 7.55, 8.87, 9.52, and 9.91 Mev. The levels at 5.51 and 6.10 Mev have not previously been detected.

INTRODUCTION

Be^9

LEVELS of Be^9 have been observed in inelastic scattering of various particles on Be^9 and in the reactions $Li^7(He^3,p)Be^9$ and $B^{10}(t,\alpha)Be^9$. The experiments are listed by Ajzenberg and Lauritsen.[1] A group of particles corresponding to a level in Be^9 at 1.8 Mev has been observed in several reactions.[2–10] Some doubt exists as to whether this group arises from a real level in Be^9 or is a result of the onset of a multi-body breakup process at the photoneutron threshold of Be^9.[4,8,10] The 2.43-Mev state has been found in almost all observations of the levels of Be^9. The 3.1-Mev state has been observed primarily in studies of the $Li^7(He^3,p)$-Be^9 and $B^{10}(t,\alpha)Be^9$ reactions.[2,3] The 4.8-Mev state has been observed in the reactions $Li^7(He^3,p)Be^9$, $B^{10}(t,\alpha)Be^9$, and $Be^9(p,p')Be^9$.[2,3,5] States of higher energy have been observed in the $Be^9(p,p')Be^9$ reaction.[5]

C^{12}

The 7.65-Mev state in C^{12} is only slightly above the threshold for breakup into an α particle and Be^8, and the state is known to breakup in this way. If the state can also decay by γ-ray emission to the ground state of C^{12}, either by a direct transition or by a cascade through the 4.43-Mev state, then this would be a process by which carbon could be formed out of helium in the stellar buildup of the elements.[11–13] Various values for Γ_γ/Γ ranging from near unity to near zero have been reported[14–18]; the results may even indicate that two levels exist in this region of excitation.

Some calculations based upon the α-particle model have predicted a 3^- level in C^{12} at 5.53 Mev.[19] A preliminary search has been reported in which this level was not found.[20]

C^{13}

In some light nuclei, Be^8 for example, the number of well verified levels has diminished over the past several years; it may be that some of the levels presently thought to be spurious will be found to exist after all. The nucleus C^{13} is a typical case. C^{13} was once thought to have levels at 0.7, 3.08, 3.68, 3.89, 4.6, 5.15, 5.60, 5.87, 6.34, and 6.78 Mev in the range up to 7 Mev.[21] More recent measurements give only the values 3.086, 3.685, 3.855, and 6.868 in this range.[22,23] As will be

† Preliminary reports of this work were given at meetings of the Americal Physical Society [C. D. Moak and A. Galonsky, Bull. Am. Phys. Soc. Ser. II, **1**, 196 (1956); Galonsky *et al.*, Bull. Am. Phys. Soc. Ser. II, **2**, 51 (1957)].
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13 E. E. Salpeter, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 2, p. 41.
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16 U. F. Hornyak, Bull. Am. Phys. Soc. Ser. II, **1**, 197 (1956).
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18 K. G. Steffen and H. Neuert, Z. Physik **147**, 125 (1957).
19 A. E. Glassgold and A. Galonsky, Phys. Rev. **103**, 701 (1956).
20 C. D. Moak and A. Galonsky, Bull. Am. Phys. Soc. Ser. II, **1**, 196 (1956).
21 F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).
22 McGruer, Warburton, and Bender, Phys. Rev. **100**, 235 (1955).
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shown, two levels, at 5.51 and 6.10 Mev, have been found in the study of the $B^{11}(He^3,p)C^{13}$ reaction.

APPARATUS

Doubly-charged He^3 ions were accelerated to energies up to 1.25 Mev in the 625-kv cascade accelerator. Targets of high purity Li^7, B^{10}, and B^{11} were furnished by the Stable Isotopes Division of Oak Ridge National Laboratory and of B^{10} and B^{11} by the Atomic Energy Research Establishment in Harwell, England. The Li^7 targets were made by melting $(Li^7)_2SO_4$ on a tantalum backing. The B^{10} and B^{11} targets were made by depositing elemental boron on thin nickel foils.

Two NaI charged-particle spectrometers were used in the experiments; the first of these, having a variable angle, has been described elsewhere.[24] The second spectrometer, designed for the p-γ coincidence work, is shown in Fig. 1. It was necessary that this spectrometer have a large solid angle and as little slit-edge scattering as possible so that very few protons from higher-energy groups would be degraded in energy to fall into the region of interest and constitute a background. A pulse-height spectrum from this counter for the case of 16-Mev protons from the $H^2(He^3,p)He^4$ reaction is shown in Fig. 2. A 3 in.×3 in. NaI γ-ray counter was used to detect γ rays from the $B^{10}(He^3,p\gamma)$-C^{12} reaction. The spectrum of protons which were in coincidence with γ rays was displayed on a 100-channel pulse-height analyzer, gated by the γ-ray counter. Ground-state protons, which are not accompanied by γ rays, gave a direct measure of the accidental rate. The proton group leaving C^{12} in its 4.43-Mev level is always accompanied by a γ ray; thus the intensity ratio of the 7.65-Mev group and the 4.43-Mev group could be taken with and without γ ray gating to derive a direct measure of the $\Gamma_\gamma/\Gamma_\alpha$ ratio for the 7.65-Mev level.

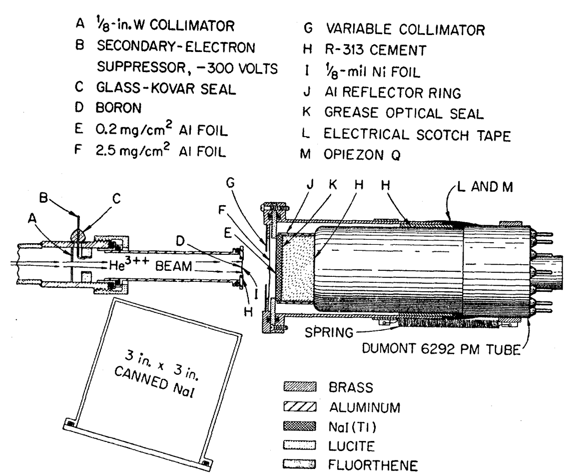

FIG. 1. The p-γ coincidence spectrometer. The wide-aperture, thin NaI proton counter was always used at 0° to the He^3 beam in order to minimize the energy spread due to center-of-mass motion.

[24] C. D. Moak and W. R. Wisseman, Phys. Rev. **101**, 1326 (1956).

RESULTS

Be^9

The proton spectrum for the $Li^7(He^3,p)Be^9$ reaction taken at a laboratory angle of 135° is shown in Fig. 3. Similar runs have been taken in 22.5° steps from 45° to 135° of laboratory angle. These data are consistent with the existence of levels in Be^9 at 1.83±0.04 Mev, 2.428 Mev (used for calibration), 3.10±0.04 Mev and 4.8±0.15 Mev. The width of the 4.8-Mev level was found to be 1.25±0.25 Mev.

Arguments have been advanced for assuming that the anomaly corresponding to a 1.83-Mev level in Be^9 does not arise from a real level but rather from the onset of three-body breakup beginning at a threshold energy of 1.667 Mev in Be^9.[9,10] The process to be considered in this case is $Li^7+He^3\rightarrow Be^8+n+p+Q$. Many assumptions can be made about the partition of the energy Q among the three particles. A derivation from statistical-mechanical arguments has been given by Uhlenbeck and Goudsmit[25]; the distribution obtained for the case of three-body breakup has the form of an ellipse. It might be expected that any specifically nuclear effects would be superimposed upon this elliptical distribution derived from phase-space considerations. Near the high-energy end of the proton spectrum the remaining two particles have low relative momentum and, thus,

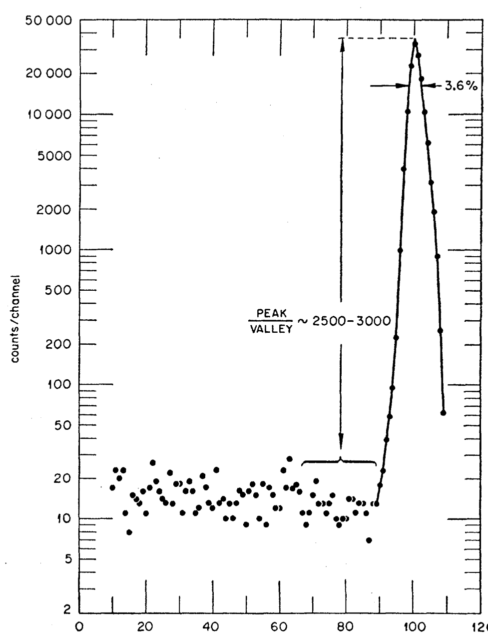

FIG. 2. Spectrum of 16-Mev protons (0°–40°) from $H^2(He^3,p)He^4$ as measured with the proton counter shown in Fig. 1.

[25] G. E. Uhlenbeck and S. Goudsmit, *Zeeman Verhandelingen* (M. Nijhoff, The Hague, 1935), pp. 201–211.

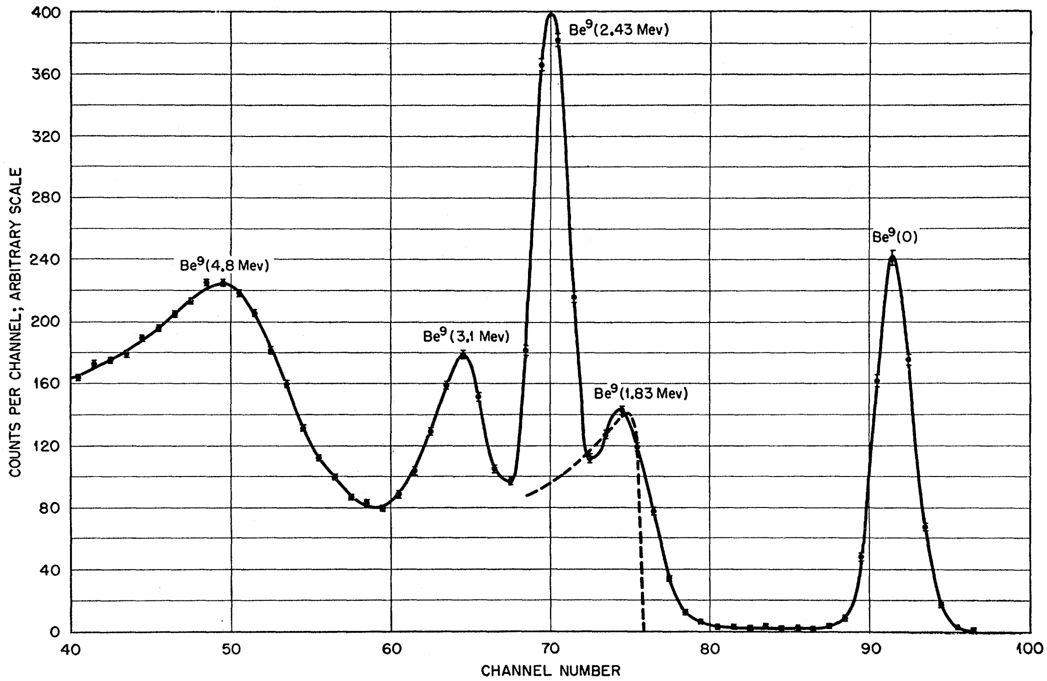

FIG. 3. Proton spectrum in the NaI spectrometer of reference 24 from the $Li^7(He^3,p)Be^9$ reaction at 135° to the He^3 beam. The protons passed through a 10.9 mg/cm² aluminum foil before entering the crystal. The dashed curve is a calculated spectrum for the reaction $He^3+Li^7\rightarrow Be^8+n+p$ for an assumed $n+Be^8$ scattering length, $a=2.3\times10^{-12}$ cm.

may interact strongly. Watson[26] has developed a theoretical description of the spectrum near the high-energy end that depends only on the scattering length, a, of the $n+Be^8$ system.

Since a is not known for $n+Be^8$, it was used as a parameter to obtain the best possible fit to the data. The spectrum for $a=2.3\times10^{-12}$ cm, shown by the dashed curve in Fig. 3, reproduces the 1.83-Mev peak except on the high-energy side where the predicted cutoff is too sharp to be seen with a crystal spectrometer. A three-body spectrum with $a=2\times10^{-12}$ cm has also been fitted to the $B^{11}(d,\alpha)Be^9$ and $Be^9(p,p')Be^9$ spectra[10] and with $a=1.3\times10^{-12}$ cm to the $Be^9(d,d')Be^9$ spectrum.[8] Although the approximate agreement in the values of a lends support to the three-body-breakup interpretation of the anomaly, no experiment has been detailed enough to rule out the possibility that the anomaly is, rather, a true representation of a level in Be^9.§

It is apparent that a similar ambiguity exists for the anomaly around channel 50 in Fig. 3. It may represent a level in Be^9 at 4.8 Mev or a three-body spectrum in which Be^8 is left in its broad, 2.9-Mev state.

[26] K. M. Watson, Phys. Rev. **88**, 1163 (1952).

§ *Note added in proof.*—Miller has recently fitted the $B^{11}(d,\alpha)Be^9$, $Be^9(p,p')Be^9$, and $Be^9(d,d')Be^9$ spectra with $a=2\times10^{-12}$ cm, and has pointed out that such a large value of a is equivalent to an s-wave ($\frac{1}{2}^+$) level near 1.7 Mev [Dan W. Miller, Phys. Rev. **109**, 1669 (1958)].

C^{12}

A proton spectrum taken at 15° with the spectrometer in Fig. 1 for the $B^{10}(He^3,p)C^{12}$ reaction is shown in Fig. 4. An expanded view of the spectrum for the levels between 9.61 Mev and 16.57 Mev in C^{12} is shown in Fig. 5. In the upper sections of the figures the energy-energy-level diagrams of Ajzenberg and Lauritsen[1] are reproduced. The 16.10-Mev level and the levels below 10 Mev were used to calibrate the energy scale of the spectrometer since the positions of these levels were already accurately determined. The two levels at 10.80 and 11.1 Mev, originally reported by Johnson,[27] were not resolved in this experiment. Levels at 14.05 Mev and 15.62 Mev now appear to be well established. Energy-level positions as determined in these experiments are shown on the arrows in Figs. 4 and 5. No previously unlisted levels were found. Absolute cross sections were determined to an accuracy of a factor of two. For reactions to the ground state the cross section at 15° is 0.7 μb/sterad at an average He^3 energy of 1.23 Mev.

The pulse-height spectrum of protons which were in coincidence with γ rays of energy greater than 1.5 Mev is shown in Fig. 6. The procedure was as follows: first a simple proton spectrum without γ-ray coincidence was run; then a coincidence count was taken to give the same number of counts in the proton group to the

[27] V. R. Johnson, Phys. Rev. **86**, 302 (1952).

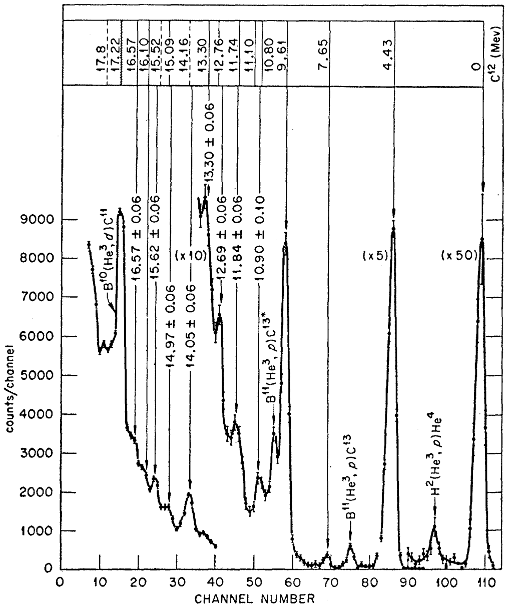

FIG. 4. Proton spectrum in the thin NaI spectrometer of Fig. 1 from the $B^{10}(He^3,p)C^{12}$ reaction. The average reaction angle is 15°. Before entering the crystal the protons passed through nickel, air, and aluminum equivalent to a thickness of 7.5 mg/cm² of aluminum.

4.43-Mev level. A proton leading to the 4.43-Mev level is always accompanied by a γ ray. Any state which does not decay every time by emission of γ rays will then have a weaker intensity relative to the 4.43-Mev group for the case of coincidence counting. This reduction in intensity corresponds to coincidences lost because the level decays by α-particle rather than by γ-ray emission. The dotted peaks in Fig. 6 show the intensities of the ground state and 7.65-Mev state proton groups relative to the 4.43-Mev state proton group for the case of simple proton counting. Since the ground-state protons are never accompanied by a γ ray, this group should completely disappear in a coincidence spectrum. The small residual peak is due to accidental counts. This accidental rate, when divided by the ratio of intensities of the 7.65-Mev state proton group and the ground-state proton group, gives an estimate of the accidental rate for the 7.65-Mev state proton group. The accidental rate for the 7.65-Mev state group is about one-tenth of the coincidence rate rate observed in the region between channel 60 and channel 70. The coincidences observed were completely accounted for by a "valley" of counts, similar to that shown in Fig. 2, coming from the 4.43-Mev state proton group. No evidence of a peak was found. Analysis of the data indicated that a peak 1.6% as intense as the dotted peak could have been observed. If the 7.65-Mev level in C^{12} has spin and parity 0^+, the radiation will consist of a cascade of two γ rays, a 4.43-Mev γ ray, and a 3.22-Mev γ ray. When the efficiency of the NaI detector is taken into account, the data indicate that $\Gamma_\gamma/\Gamma<0.9\%$. If the level makes a direct transition to the ground state, a single, 7.65-Mev γ ray will replace the cascade; in this case the data indicate that $\Gamma_\gamma/\Gamma<1.4\%$.

Rough estimates were obtained for the γ-α branching ratios of the 12.69-Mev and 14.97-Mev levels using the same procedures as were used for the 7.65-Mev

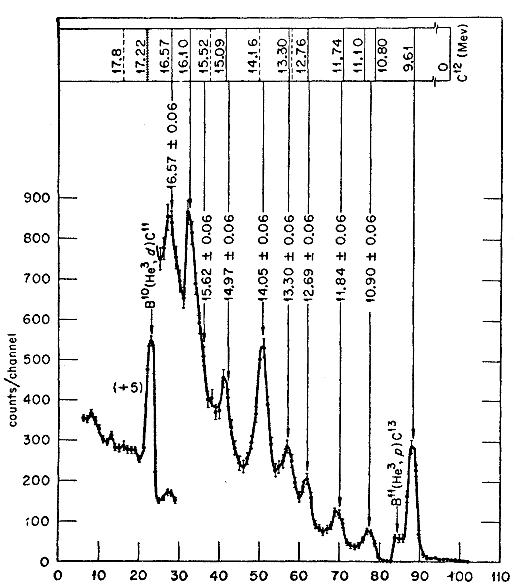

FIG. 5. Proton spectrum expanded to show levels from 9.61 to 16.57 Mev in C^{12}. See caption for Fig. 4.

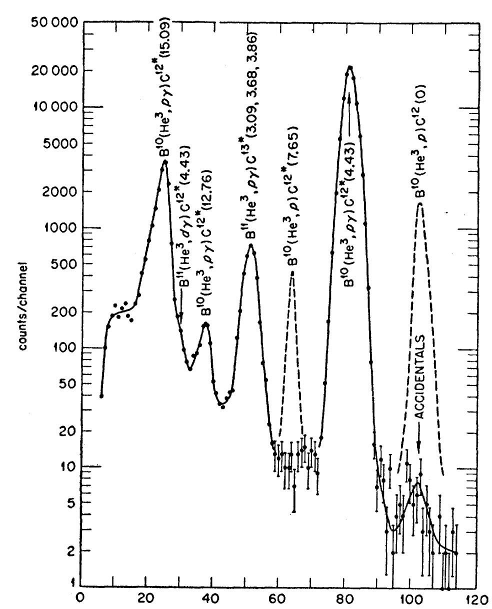

FIG. 6. Spectrum of protons (0°−40°) in coincidence with γ rays (~100°–150°, $E_\gamma>1.5$ Mev) from $B^{10}+He^3\rightarrow p+C^{12*}\rightarrow p+C^{12}+\gamma$. Coincidence spectrometer is shown in Fig. 1.

level. Values obtained for Γ_γ/Γ were $3\pm1\%$ for the 12.69-Mev level and $50\pm25\%$ for the 14.97-Mev level.

C^{13}

The proton spectrum for the $B^{11}(He^3,p)C^{13}$ reaction, obtained at 13° with the counter in Fig. 1, is shown in Fig. 7. The positions of the peaks indicate levels in general agreement with previously quoted values,[22] although the level at 8.4 Mev in C^{13} was not observed and the three levels around 7.55 Mev were not resolved. Special calibration runs were made using absorbers to subtract out most of the energy from the proton groups to the 3.68-Mev and 3.86-Mev levels. These levels were resolved and the 3.68-Mev level group was found to be 1.3 times as intense as the 3.86-Mev level group. When unresolved, the composite group would give the appearance of a single level in C^{13} at 3.74 Mev. This composite group, along with the groups to the ground state, the 3.09-Mev state and the 6.87-Mev state, were used to calibrate the spectrometer. For the spectrum at 13°, Fig. 7, the target thickness was known well enough to determine the absolute cross sections to an accuracy of a factor of two. For reactions to the ground state the cross section is 2.2 μb/sterad at an average He^3 energy of 1.23 Mev.

Two groups of protons corresponding to previously unobserved levels in C^{13} at 5.51 Mev and 6.10 Mev were found. The levels of C^{13} have been studied recently by

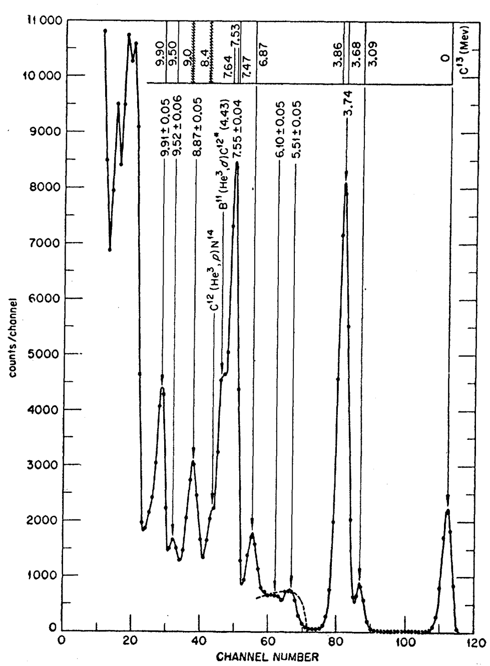

FIG. 7. Proton spectrum in the thin NaI spectrometer of Fig. 1 from the $B^{11}(He^3,p)C^{13}$ reaction. The average reaction angle is 13°. Before entering the crystal the protons passed through nickel, air, and aluminum equivalent to 8.8 mg/cm² of aluminum. The dashed curve is a calculated spectrum for the reaction $He^3+B^{11}\rightarrow C^{12}+n+p$.

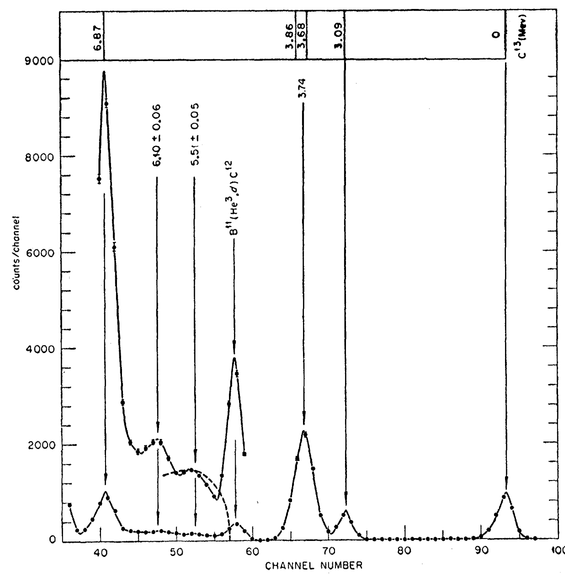

FIG. 8. Proton spectrum in the NaI spectrometer of reference 24 from the $B^{11}(He^3,p)C^{13}$ reaction at 135° to the He^3 beam. The protons passed through a 25.0-mg/cm² aluminum foil before entering the crystal. The dashed curve is a calculated spectrum for the reaction $He^3+B^{11}\rightarrow C^{12}+n+p$.

magnetic analysis of the protons from the $C^{12}(d,p)C^{13}$ reaction[23]; no levels were found between 3.86 Mev and 6.87 Mev. It appeared likely that the two proton groups being reported here were due to a contaminant in the target. The two groups were proved to be protons by passing them through varying amounts of Al absorber; variation of residual energy with absorber thickness showed that the peaks were due to protons and not deuterons or α particles. Reactions of He^3 on Li^6, Li^7, Be^9, B^{10}, C^{12}, C^{13}, N^{14}, N^{15}, O^{16}, and O^{17} were considered for possible proton groups which would fall at the right energy to explain the two groups found in the $B^{11}(He^3,p)C^{13}$ spectrum. Of these only Li^7, Be^9, and B^{10} give proton groups near the energies of the proton groups involved here. To eliminate Be^9 observations were taken at different laboratory angles. If a proton group due to Be^9 had appeared in the $B^{11}(He^3,p)C^{13}$ spectrum, the energy of the group would have shifted with laboratory angle with respect to the groups due to the $B^{11}(He^3,p)C^{13}$ reaction. The spectrum shown in Fig. 8 was observed at 135°. An absorber of 25.0-mg/cm² Al was used so that the proton groups could be displayed on an expanded scale. Level positions, as calculated from the data taken at 135°, agree with the positions calculated from the data taken at 13°. If either of the groups had been due to Be^9, there would have been a shift in the derived level position of more than 0.25 Mev. To eliminate Li^7 as a contaminant we note that the shift with angle would be even greater than for Be^9. In addition, a search was made for a higher-energy proton group which would have appeared in a part of the spectrum not having any groups due to

B^{11}; no evidence of Li^7 contamination was found. To eliminate B^{10} as a contaminant a direct subtraction method was used. Since a small amount of B^{10}, 0.04%, was present in the B^{11} targets, several proton groups due to B^{10} were found. The intensities of these groups were measured and, with a knowledge of the complete spectrum due to B^{10}, a direct subtraction of the B^{10} contribution was made. The contribution due to B^{10} in the region of the 5.51-Mev and 6.10-Mev levels in C^{13} was less than 2%, and subtraction of the B^{10} contribution did not alter the shape of the spectrum.

As a final check of possible contaminants, the targets were examined spectroscipically for Li and Be contamination by Dr. Feldman of the Chemistry Division. No trace of Li or Be was found, indicating that contamination by Li or Be was less than 0.02% of the target material. Chemical analysis by Dr. Thomasen of the Chemistry Division indicated a trace of N^{14} amounting to less than 0.1% of the target material. Carbon contamination was shown to be small by the absence of peaks in the spectrum due to the $C^{12}(He^3,p)N^{14}$ reaction; in addition the proton groups from the reaction do not have the right energies to cause difficulty.

The fact that the two new levels in C^{13}, at 5.51- and 6.10-Mev excitation, have not been observed in n-C^{12} total cross-section measurements[28] indicates that the levels are both narrow, probably less than 10 kev. We may tentatively correlate one of the levels with a $\frac{5}{2}-$ level predicted by Kurath[29] from shell-model calculations of the $1p$ nucleons to lie between 4 and 5 Mev. If the 5.51-Mev level is the predicted level, then it could be formed with 0.61-Mev f-wave neutrons on C^{12}. The experimental width for a radius 4.5×10^{-13} cm would then be 2.5 kev for a single-particle level and much less than 2.5 kev for the level in question which involves the excitation of p nucleons and may, therefore, have a very small reduced width for $f_{\frac{5}{2}}$ neutrons. If the 6.10-Mev level is the predicted level, then its width would be much less than 28 kev. In either case the level would have escaped observation. It is to be noted that whichever (if either) is the $\frac{5}{2}-$ level, its excitation energy is somewhat greater than predicted.

The only other experiment that we are aware of in which these levels could have been detected is that of Green and Middleton[23] who examined by magnetic analysis the proton spectrum at 15° from $C^{12}(d,p)C^{13}$ with 9-Mev deuterons. They did not observe any new levels although their data indicate that a sharp group corresponding to a level between 3.86 and 6.87 Mev could easily have been detected if its intensity had been as much as 5% of that of the ground-state group. Since the conditions of their experiment were such that stripping would be expected to be the dominant mode of the reaction, they would have had difficulty in seeing a level with a small neutron reduced width (to which the stripping cross section is proportional).

If the two levels exist at the same excitation energies in N^{13} as in C^{13}, then the light binding of a proton to N^{13}, 3 Mev less than a neutron to C^{13}, may broaden the levels considerably in p-C^{12} scattering as compared with n-C^{12} scattering even though a Coulomb barrier will be present. For a $\frac{5}{2}-$, single-particle level at 5.5 Mev in N^{13} the proton energy is 3.86 Mev and the experimental width is $\sim$0.3 Mev if the radius is 4.5×10^{-13} cm. As the proton scattering has been studied as a function of energy in 6-kev steps up to 4.35 Mev[30] and in 25-kev steps from 4.4 to 5.5 Mev,[31] an upper limit to the proton reduced with is $\sim$2% of the single-particle width for Kurath's $\frac{5}{2}-$ level.

In view of the ambiguity encountered in interpreting the anomaly near the neutron threshold in the Be^9 spectrum it seems appropriate to ask whether the anomaly in the C^{13} spectrum, which we have referred to as a level at 5.51 Mev, could, in fact, be a manifestation of 3-body breakup. The neutron threshold, at 4.95 Mev in C^{13}, is so low that use of the zero-energy n-C^{12} scattering around 5.5 Mev will not be very accurate. Fortunately the n-C^{12} scattering is known[28] and Thomas[32] has fitted the data up to 0.9 Mev with the effective-range theory. From this fit we have extracted a scattering length of 6.1×10^{-13} cm and an effective range of 3.0×10^{-13} cm. Inserting these values into Watson's[26] Eqs. (29) and (33) we have calculated the resulting proton spectra at 13° and 135° for the reaction $He^3+B^{11}\rightarrow C^{12}+n+p$. These spectra, which are the dashed curves in Figs. 7 and 8, have peaks which are broader and less symmetrical than observed.

Since it is always possible that some other 3-body theory would fit the data, we cannot definitely exclude a 3-body interpretation of the 5.51-Mev level from this experiment. Certainly a high-resolution experiment, say with a magnetic analyzer, should be definitive. To be considered a level the anomaly must be sharp enough to be in accord with its nonobservation in scattering experiments. Otherwise, 3-body mechanisms must be further investigated, since Watson's theory does not fit even the present low-resolution data.

[28] D. W. Miller, Phys. Rev. **78**, 806 (1950).
[29] Dieter Kurath, Phys. Rev. **101**, 216 (1956).
[30] H. L. Jackson *et al.*, Phys. Rev. **89**, 365 (1953).
[31] Reich, Phillips, and Russell, Phys. Rev. **104**, 143 (1956).
[32] R. G. Thomas, Phys. Rev. **88**, 1109 (1952).