Carbon-10 and Mass Measurements for Light Nuclei*

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The mass excess of ^{10}C and the excitation energy of its first excited state have been measured using the $^{10}B(^3He,t)^{10}C$ reaction. The results confirm one of three earlier measurements which gave the mass excess as 15.7025±0.0018 MeV, and an average of all relevant measurements for the energy of the first excited state yields 3.344±0.008 MeV. These values differ significantly from those previously accepted, and since they provided energy calibrations for measurements on a number of light nuclei, appropriately revised results are quoted for the mass excess of ^{37}Ca, as well as for the energies of the second excited state in ^8B and $T=\frac{3}{2}$ states in ^7Be, ^{21}Na, and ^{37}K.

I. INTRODUCTION

ACCURATE values now exist for the excitation energies of the $T=2$ analog states in ^{20}Ne and ^{24}Mg. These states have been observed as final states in (p,t) and $(^3He,n)$ reactions,[1] and as compound nuclear resonances appearing in proton-induced reactions.[2] For both nuclei, the averages of values for these excitation energies compiled[3] from all available sources are accurate to better than ±5 keV.

A recent investigation of analog states throughout the $(1d_{5/2})$ shell[4] included a remeasurement of the (p,t) and $(p,^3He)$ reactions on ^{22}Ne and ^{26}Mg targets in which carbon impurities had been added to provide an energy calibration. In particular, the ground and first excited states of ^{10}C, produced in the reaction $^{12}C(p,t)^{10}C$, result in triton peaks whose energies bracket that of the $T=2$ states in ^{20}Ne and ^{24}Mg. Since the ground-state mass of ^{10}C taken from the current mass table[5] was 15.658 MeV with a quoted error of ±13 keV, it was therefore surprising to observe a discrepancy of ~45 keV with the accepted energies of the $T=2$ states. This has led to the present reevaluation of the mass of ^{10}C, and the energy of its first excited state.

There have been three previous measurements[6–8] of the mass of ^{10}C, and these are summarized in Table I. Only the first two results are included in the average value quoted in Ref. 5. Although the error bar on the third measurement is significantly smaller than the others, the fact that it differed from them by ~45 keV, while using a similar experimental method, made it desirable to perform an independent measurement of a different type. For this purpose, the reaction $^{10}B(^3He,t)^{10}C$ was chosen.

II. EXPERIMENTAL PROCEDURE

The experiment was carried out using the external beam of the Berkeley 88-in. spiral-ridge cyclotron. A diagram and general description of the experimental layout have been given elsewhere.[9] The beam was magnetically energy-analyzed by being deflected 40° and passed through a 1-mm slit. It was then focused to a spot 2 mm×2 mm on a target at the center of the scattering chamber. The exact angle at which the beam intersected the target was measured using two luminous foils, one at the target position, and the other 70 cm downstream. The beam energy was inferred from measuring its range in aluminum.

Reaction products were detected in two independent counter telescopes on opposite sides of the beam. Each consisted of a 150-μ phosphorus-diffused silicon ΔE transmission counter and a 3.0-mm lithium-drift silicon E counter operated in coincidence, followed by a 500-μ lithium-drift silicon E-reject counter operated in anticoincidence to eliminate long-range particles. The signals from these telescopes were fed to Goulding-Landis particle identifiers,[10] producing output signals

TABLE I. Previous measurements of the mass of ^{10}C.

Experiment	Reference	Mass excess (MeV)
(p,n) threshold	a	15.663±0.025
β^+ end point	b	15.656±0.015
(p,n) threshold	c	15.7025±0.0018

a Reference 6.
b Reference 7.
c Reference 8.

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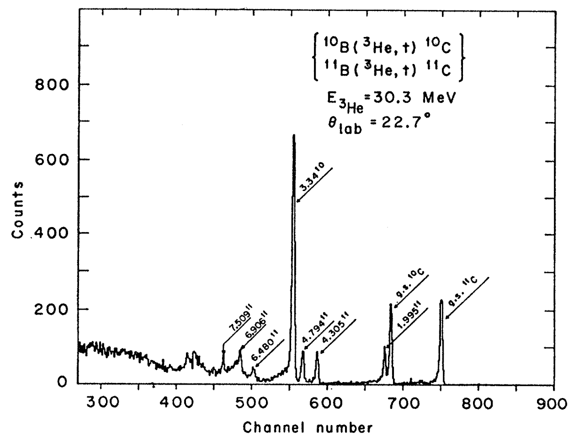

FIG. 1. A triton energy spectrum obtained at $\theta_{lab}=22.7°$, from a boron target 92% enriched in ^{10}B.

characteristic of the particle type, and the corresponding energy signals were routed accordingly into 1024-channel groups of a 4096-channel analyzer. In addition to the telescopes, two single 1-mm "monitor" counters were mounted at $\theta_{lab}=+27.5°$ and $-18.0°$. The angular resolution of the telescopes and monitors was about 0.25°.

Figure 1 shows the energy spectrum of tritons observed from the (^{3}He,t) reaction on a 280-μg/cm^2 boron target, 92% enriched in ^{10}B. The ^{3}He beam energy was measured to be (30.3±0.2) MeV, and the laboratory angle, after correction for a measured "beam angle" of $-0.4°$, was $+22.7°$. It can be seen from the figure that the energy of the triton peak corresponding to the ground state of ^{10}C is about 200 keV greater than that of the peak corresponding to the first excited state of ^{11}C ($E_x=1.995\pm0.003$ MeV).[11] Similarly, the first excited state of ^{10}C appears close to the second and third

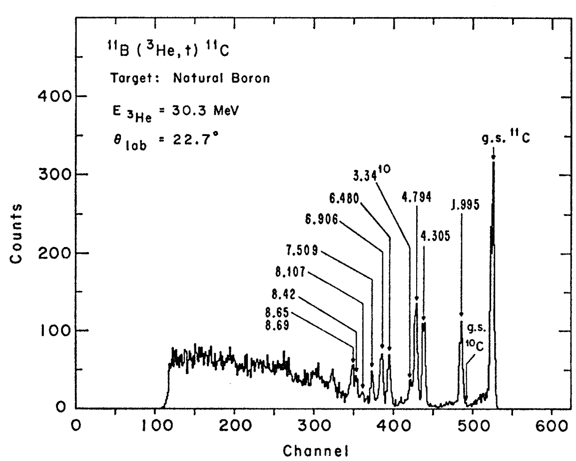

FIG. 2. A triton energy spectrum obtained from a natural boron target at $\theta_{lab}=22.7°$.

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TABLE II. Summary of results from the $^{10}B(^3He,t)^{10}C$ reaction measuring the ground and first excited states of ^{10}C.

	Telescope 1 Mass excess for:			Telescope 2 Mass excess for:		
Run No.	θ_{lab}	ground state (MeV)	1st excited (MeV)	θ_{lab}	ground state (MeV)	1st excited (MeV)
1	+22.7	15.695	19.041	−60.1	15.708	19.052
2	−21.9	15.702	19.045	−60.1	15.704	19.048
3	+22.7	15.701	19.036	−60.1	15.703	19.054
4	+18.3	15.692	19.039	−55.2	15.700	19.036

Weighted over-all averages:
^{10}C ground state (+15.700±0.010) MeV
^{10}C 1st excited state (+19.042±0.015) MeV

excited states of ^{11}C ($E_x=4.305\pm0.006$ MeV and 4.794 ±0.006 MeV).[11] Kinematic calculations for peaks in this region show a change in the energy of ^{10}C peaks relative to those from ^{11}C of about 10 keV per deg, and thus, if the Q values for the production of states in ^{10}C are to be determined by comparison with known states in ^{11}C, a precise knowledge of the laboratory angle must be maintained. Consequently, during this and all other runs, elastically scattered ^{3}He particles were recorded in the fixed monitor counters. Prior measurements of the (^{3}He,^{3}He) cross section had shown variations of ~60 and ~13% in absolute magnitude per deg change in scattering angle at $\theta_{lab}=18.0°$ and 27.5°, respectively. For this reason, an integration of the elastically scattered particles, monitored frequently throughout a run, permitted a continuous sensitive determination (to about 0.1°) of variations in the beam angle. No beam-angle excursions were detected during any of the experiments.

As a further precaution, in two runs spectra were recorded with counter-telescope 1 set at the same nominal angle on opposite sides of the beam, while telescope 2 remained fixed at $\theta_{lab}=-60.1°$ to detect any significant beam energy change. It will be shown in the following section that the peak energies extracted from these runs were consistent with the independent determinations of the laboratory angle. Additional spectra using the enriched boron target were also taken at $\theta_{lab}=+18.3°$ and $-55.2°$, and for comparison, a 500-μg/cm^2 natural boron target was bombarded at the

TABLE III. Summary of experimental data on the first excited state of ^{10}C.

Experiment	Reference	Mass excess (MeV)
$^{10}B(^3He,t)^{10}C$	a	19.028±0.030
(p,n) threshold	b	19.039±0.020
γ decay	c	19.053±0.010[d]
$^{10}B(^3He,t)^{10}C$	this work	19.042±0.015
Average		19.047±0.008

[a] Reference 13.
[b] Reference 14.
[c] Reference 15.
[d] This measurement was of the excitation energy rather than the mass excess; it has been converted using the best value for the ground-state mass excess of ^{10}C (15.703 MeV).

TABLE IV. Original and revised experimental values that depend for calibration upon the ground and first excited states of ^{10}C.

Reaction	Reference	Measured	Previous value (MeV)	New value (MeV)
$^{40}Ca(^{3}He,^{6}He)^{37}Ca$ (g.s.)	a	Mass excess	-13.24 ± 0.05	-13.23 ± 0.05
$^{9}Be(p,t)^{7}Be^{*}$ $(T=\frac{3}{2})$	b	excitation	10.97 ± 0.04	11.01 ± 0.04
$^{10}B(p,t)^{8}B^{*}$ (2nd excited)	b	excitation	2.33 ± 0.04	2.34 ± 0.04
$^{23}Na(p,t)^{21}Na^{*}$ $(T=\frac{3}{2})$	a	excitation	8.92 ± 0.03	8.97 ± 0.03
$^{39}K(p,t)^{37}K^{*}$ $(T=\frac{3}{2})$	a	excitation	5.035 ± 0.025	5.046 ± 0.025

[a] Reference 9.
[b] Reference 16.

same energy. A spectrum from the latter target, taken at $\theta_{lab}=22.7°$, is shown in Fig. 2.

III. RESULTS AND DISCUSSION

The data were analyzed, using the computer program LORNA.[12] This program establishes an energy scale by finding a least-squares fit to peaks whose Q values are known, after correcting all incoming and outgoing particles for kinematic effects and absorber losses. The states taken as known were the ground and first three excited states of ^{11}C. Although the energy scale was determined by these states at all observed angles, the unknown states were evaluated independently at each angle, and the results for the ^{10}C ground and first excited states are listed in Table II. The weighting for each individual measurement used in calculating the average was determined from the counting statistics.

A comparison of our final result in Table II with the measurements listed in Table I shows the former to be consistent with the value obtained in Ref. 8 and inconsistent with the values obtained in Refs. 6 and 7. Thus we confirm the mass excess of ^{10}C to be (15.7025 $\pm$0.0018) MeV.

There have been three previous measurements[13–15] relating to the first excited state of ^{10}C; two have determined its mass excess, and the other its excitation energy. Using the correct ground-state mass excess, good agreement is obtained among these measurements and the value derived in Table II. A summary of all experimental data on this state is given in Table III, together with the averaged result; this corresponds to an excitation energy of (3.344 ± 0.008) MeV.

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An earlier investigation[13] of the reaction $^{10}B(^{3}He,t)^{10}C$ observed states in ^{10}C at (5.28 ± 0.06) and (6.58 ± 0.06) MeV, and made a tentative identification of states at 5.03 and 5.60 MeV. An examination of all angles taken in this experiment confirms the existence of states at 5.28 and 6.58 MeV; however, we see no indication of the other two states. In fact, it should be noted that at a bombarding energy of 30 MeV and $\theta_{lab}=30°$ (the experimental conditions in Ref. 13) the peaks observed in the spectrum of Mangelson *et al.* would correspond exactly to states in ^{11}C at 6.906 and 7.509 MeV. Similar peaks are observed in our spectrum of Fig. 1 and by comparison with Fig. 2 it is evident that they can be adequately accounted for as being entirely due to these states in ^{11}C. Thus, the tentative assignment of states at 5.03 and 5.60 MeV in ^{10}C should be dropped.

The earlier values for the masses of the ground and first excited states of ^{10}C were used in determining the energies of analog states and certain mass excesses for a number of light nuclei. Thus, the results of these measurements must be changed to take account of the revised ^{10}C masses. Table IV lists references,[9,16] previous values, and the revised excitation energies for those earlier measurements that were sufficiently precise to warrant adjustment. Not all values have been changed by as much as 45 keV since in most cases ^{10}C was not the only source of calibration. Not listed in the table are the $T=2$ states in ^{20}Ne and ^{24}Mg whose measurement, as discussed earlier, first indicated that a discrepancy existed; using ^{10}C for calibration the derived excitation energies of these states are within 10 keV of the accepted values (providing final confirmation of the present results).

ACKNOWLEDGMENT

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