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Abstract

The $^{6}$Li($^{3}$He,t)$^{6}$Be and $^{10}$B($^{3}$He,t)$^{10}$C reactions have been studied at E($^{3}$He) = 30 and 40 MeV. In $^{6}$Be, an excited state is observed at $E_x$ = 1.67 ± 0.08 MeV ($\Gamma$ = 1.13 ± 0.08 MeV). In $^{10}$C, in addition to the sharp ground and first excited states, level structure centered at $E_x$ = 5.28 and 6.58 MeV is observed.

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[††]J. Simon Guggenheim Fellow 1965-1966; now at Haverford College, Haverford, Pennsylvania.

## 1. Introduction

Experimental evidence on the level structure of the A = 6 isobaric triad is rather sparse[1]). In $^{6}$He only one excited state ($E_x$ = 1.797 ± 0.025 MeV, $\Gamma$ = 113 ± 20 keV) has been located with any degree of certainty. In $^{6}$Li, the corresponding T = 1 state has probably been observed ($E_x$ = 5.36 ± 0.015 MeV, $\Gamma$ = 320 ± 50 keV), but no other T = 1 states have been found at higher excitations. The level structure of the mirror nucleus of $^{6}$He, $^{6}$Be, has until recently been completely unknown. The reasons for this have been twofold: $^{6}$Be is unstable with respect to breakup into $^{4}$He + 2p by 1.373 MeV, and the binding energies for breakup into $^{5}$Li + p and $2^{3}$He are, respectively, 0.592 and 11.487 MeV, insuring that any excited states have at least two energetically possible decay modes. The reactions leading to $^{6}$Be are $^{3}$He($\alpha$,n)$^{6}$Be ($Q_n$ = 9.091), $^{6}$Li(p,n)$^{6}$Be ($Q_m$ = -5.070) and $^{6}$Li($^{3}$He,t)$^{6}$Be ($Q_m$ = -4.306). On the one hand the fact that all states of $^{6}$Be are unbound means that they will all have intrinsic widths which are likely to become considerable for highly excited states. On the other hand, the negative Q-values and the relative difficulties in detecting neutrons and tritons have inhibited the studies of the nuclear reactions leading to $^{6}$Be.

There had been reports[2,3]) in studies of the two neutron reactions of an excited state at $E_x \approx 1.5$ MeV, which would correspond to the known T = 1 states in $^{6}$He and $^{6}$Li at 1.80 and 5.36 MeV. However, a study of the ($^{3}$He,t) reaction at E($^{3}$He) = 12 MeV had failed to show evidence for any excited states of $^{6}$Be with $\Gamma < 1$ MeV below $E_x$ = 2.8 MeV[4]). Furthermore in a study[5]) of thresholds in the $^{6}$Li(p,n)$^{6}$Be reaction, only the ground-state threshold was observed

up to $E_x \approx 3.8$ MeV. On the other hand, investigators studying[6]) the $^6Li(p,n)^6Be$ reaction at several angles at proton energies of 30 and 50 MeV reported nine excited states of $^6Be$ with $E_x \leq 16.3$ MeV, including three with $E_x < 3.8$ MeV.

Recently studies[7]) of the $^4He(^3He,n)^6Be$ ($E(^3He) = 26$ MeV) and $^6Li(p,n)^6Be$ ($E_p = 11.6$ and 12.6 MeV) reactions have shown that below $E_x \approx 5.7$ MeV, there is only one excited state, at $E_x = 1.6 \pm 0.1$ MeV and $\Gamma = 1.1 \pm 0.2$ MeV[†]. The study of the $^6Li(^3He,t)^6Be$ reaction reported here permits a redetermination of the energy parameters of this state, and permits an investigation of the level structure of $^6Be$ up to $E_x \approx 13$ MeV.

The structure of the A = 10 isobaric triad is much better known[1]) than that for A = 6. Below $E_x = 12$ MeV, eleven T = 1 states have been located in $^{10}Be$, and approximately eight such states have been located in the corresponding excitation region in $^{10}B$: see table 1. On the other hand, in $^{10}C$, which, until now, has been studied only through the $^{10}B(p,n)^{10}C$ ($Q_m = -4.388$) and $^{12}C(p,t)^{10}C$ ($Q_m = -23.319$) reactions, only one excited state ($E_x = 3.360 \pm 0.017$ MeV[8,9]) has been located with any certainty. States at 5.6 ± 0.1, (7.2 ± 0.2) and 10.2 ± 0.2 MeV ($\Gamma \approx 1.5$ MeV) have also been reported[10]). We will report on a preliminary study of the $^{10}B(^3He,t)^{10}C$ reaction ($Q_m = -3.624$ MeV) and on the location of excited states of $^{10}C$. All excited states of $^{10}C$ above the 3.36-MeV state are energetically unbound with respect to decay into 2α + 2p ($E_b = 3.770$),

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[†] P. C. Rogers and H. E. Wegner (Bull. Amer. Phys. Soc. 11 (1966) 301, and private communication) have reported on a study of the $^6Li(^3He,t)^6Be$ reaction at 30 MeV. Their preliminary values for the parameter of the first excited state are $E_x = 1.63 \pm 0.1$ MeV and $\Gamma = 1.5 \pm 0.2$ MeV.

$^{9}B + p$ ($E_b = 4.050$), $^{6}Be + \alpha$ ($E_b = 5.143$) and $^{5}Li + \alpha + p$ ($E_b = 5.735$). This means, of course, that particle groups to such excited states must be observed above a many particle continuum background.

## 2. Experimental Procedure and Results

### 2.1. EXPERIMENTAL SETUP

A beam of $^{3}He$ particles accelerated in the 88-inch Berkeley cyclotron entered a 36-inch-diameter scattering chamber[11]). A target holder located at the center of the chamber held a quartz slit, used in aligning the beam and checking on its dimensions, and four targets. The height of the target holder assembly was set by remote control, and any desired target could be brought into position to be bombarded by the incident beam.

The charged particles emitted in the interaction of the $^{3}He$ beam with the target nuclei were viewed by counter telescopes located at two angles to the incident beam. Each of the counter telescopes consisted of a dE/dx and an E counter. An identifying system of the type described by Goulding et al.[12] was used. Typically the dE/dx counter was an 8-mil thick Si detector, while the E counter was 120 mils thick. 400-channel RIDL analyzers were used to record the identifier spectrum, the spectrum in a monitor counter, and the "valley" between the pulses due to deuterons and to tritons entering the counters. The spectra of the tritons and of the $^{3}He$ particles in each of the two counter systems were fed into four separate 1024-channel configurations of a Nuclear Data pulse-height analyzer. A block diagram of the system has been described previously[13]).

At the conclusion of each run, these 4096 channels were dumped into the memory of a PDP5 computer. The computer was programmed to display the spectra visually on a scope, record them on tape, and graph them on a Cal-Comp plotter. For each run, triton and $^3$He spectra were thus obtained at two angles.

If the runs were longer than two or three hours, the data were dumped at intervals of about two hours and later added for a composite spectrum from the entire running period. This was done to prevent the possibility of electronic drifts decreasing the resolution of the system. A slow pulser fed a signal simulating a high-energy triton group into each triton spectrum. The peak channel and width of the group were used to observe electronic drifts. For total runs of six to eight hours, the channel positions of reference peaks did not shift by more than half a channel from their average value.

The $^3$He spectra were used to observe beam energy shifts and to identify impurities in the targets. The peak channels of the oxygen and carbon impurities observed in the $^3$He spectra in different runs at the same angles were used to identify system shifts. Although no significant shifts of energy or electronics were noted during long runs on a given target at a fixed angle, in a few cases shifts between runs on different targets or on one target at different angles were noted. In all cases where correction for such shifts was made, at least two of the following three indications were observed: (a) a shift in the slow pulser peak; (b) a relative shift in the $^3$He spectra peak channels of both the oxygen and carbon impurity peaks in the various targets run at the same angle; (c) a shift of all the identifiable peaks in the $^3$He spectrum away from the average $^3$He energy scale.

The energy of the incident $^{3}$He beam was determined to first order by observing the range of the $^{3}$He particles in aluminium[14]). For energy measurements the target holder was lowered and the beam was allowed to hit aluminum layers of known thicknesses in two remotely operated absorber wheels located at the entrance of the Faraday cage. Although this energy was only approximate, it could be used as an approximate input value in an IBM 7094 computer program called LORNA†. Input for this program included the channel positions and Q-values of known elastic and inelastic $^{3}$He groups, and of known triton groups from target nuclei and from the usual oxygen and carbon contaminants. Triton and $^{3}$He data were analyzed separately. The program calculated the least-square dependence of particle energy on channel number in each of the two counter systems. In addition, LORNA calculated the Q-values of any unknown peaks from these parameters. The Faraday cage mentioned earlier was used to determine the number of $^{3}$He particles hitting the target. It was calibrated approximately once every day of running time, and the number of incident $^{3}$He particles is believed to be known to ± 4 percent. The alignment of the beam was also determined once a day, and the angles at which the counters were nominally positioned was suitably corrected for the "0°" position of the beam.

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†We are grateful to Mr. Creve Maples, Jr., for permission to use this program, and help in initiating us into its mysteries.

The $^{6}Li$ and $^{10}B$ targets[†] were self-supporting foils. Both were separated isotopes: the lithium was 99.3% $^{6}Li$ and the boron was 96% $^{10}B$. The $^{6}Li$ targets which were used ranged in thickness from 127 to 180 $\mu g/cm^2$. The $^{10}B$ target was $\approx$ 140 $\mu g/cm^2$ thick. $^{12}C$ foils which were used for calibration purposes ranged from 150 to 300 $\mu g/cm^2$. These thicknesses correspond to full-width energy losses of 15 to 35 keV for the incident $^{3}He$ energies involved in these experiments.

## 2.2. THE $^{6}Li(^{3}He,t)^{6}Be$ REACTION

Figure 1 shows a part of the triton spectrum at $E(^{3}He)$ = 39.4 MeV, $\theta$ = 40°, from the $^{6}Li(^{3}He,t)^{6}Be$ reaction. Additional spectra have also been obtained at $E(^{3}He)$ = 30.6 MeV ($\theta$ = 35° and 55°), 39.4 MeV ($\theta$ = 20°, 50° and 70°) and 40.1 MeV ($\theta$ = 30°). The spectra all show the triton groups corresponding to the (92 ± 6)-keV-wide[1]) ground state of $^{6}Be$ and to the broad first excited state[7]). These groups are observed over a smooth many-particle continuum[††].

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[†] The $^{6}Li$ targets were prepared by C. E. Ellsworth and D. J. O'Connell of LRL; the $^{10}B$ targets by S. H. Maxman of the University of Pennsylvania. We acknowledge with thanks their invaluable help. The separated isotopes were furnished by the Stable Isotopes Division of ORNL.

[††] Some high points in the continuum region are due to tritons from the $^{16}O(^{3}He,t)^{16}F$ reaction to various known excited states of $^{16}F$ (see, e.g., C. D. Zafiratos, F. Ajzenberg-Selove and F. S. Dietrich, Phys. Rev. 137 (1965) B1479, and R. H. Pehl and J. Cerny, Phys. Lett. 14 (1965) 137). The origin of these tritons was also checked by deliberately oxidizing one of the $^{6}Li$ targets and observing the triton spectrum under those circumstances.

Assuming that the continuum background in the region of the first excited state is as shown by the dashed line, we find

$$E_x = 1.67 \pm 0.08 \text{ MeV, and}$$

$$\Gamma = 1.13 \pm 0.08 \text{ MeV.}$$

The errors quoted involve the uncertainties in the true shapes of the groups due to the background subtraction, as well as the usual statistical uncertainties, and the errors in the $(Q_o - Q_1)$ determination which result from uncertainties in the values of the mean $^3$He energy within the target and in the shape of the triton energy versus channel position curve. The width of the excited state has been calculated taking into account the inherent width of a triton group due to a sharp state: under the conditions of these runs, this "sharp" width at half maximum is $\approx$ 200 keV.

Our values for the energy parameters of the first excited state, $E_x$ = 1.67 ± 0.08 MeV, $\Gamma$ = 1.13 ± 0.08 MeV, may be compared with the values $E_x$ = 1.6 ± 0.1 MeV $\Gamma$ = 1.1 ± 0.2 MeV reported earlier[7]). From the type of final-state interaction calculations discussed by Yu and Meyerhof[15]), excitation energies of broad states may appear to be different in different reactions. The shifts may be of the order of the width of the state[16]). A shift outside the quoted uncertainties in the excitation energy of the 1.7 MeV state of $^6$Be has not been observed in the $^4$He($^3$He,n)$^6$Be, $^6$Li(p,n)$^6$Be and $^6$Li($^3$He,t)$^6$Be reactions.

No triton groups have been observed at any of the angles of observation corresponding to the many $^{6}$Be states reported by Batty et al.[6] below $E_x \approx 13$ MeV, with the exception of their 1.82 ± 0.12 MeV state, which may correspond to the broad 1.67 MeV state observed earlier[7] and in this work.

In the reaction $^{6}$Li($^{3}$He,t)$^{6}$Be at E($^{3}$He) = 39.4 MeV differential cross section for formation of the ground state of $^{6}$Be are 400 ± 100 and 190 ± 50 μb/sr at 31.3° and 61.6° c.m. The angular distribution of the ground state tritons dips to ≈ 50 μb/sr at ≈ 50°, c.m., rises to a secondary maximum at ≈ 60°, c.m., decreases to a second minimum at ≈ 80°, c.m., and then gently rises to the largest angle studied, ≈ 100° c.m. At 31.7° c.m. the differential cross section for formation of the 1.67 MeV state of $^{6}$Be is approximately the same as for the ground state; at 62.0° c.m., the cross section is ≈ 0.5 mb/sr.

## 2.3 THE $^{10}$B($^{3}$He,t)$^{10}$C REACTION

Figure 2 shows a portion of the triton spectrum at E($^{3}$He = 30.6 MeV, $\theta = 30°$. A second run was also made at E($^{3}$He) = 40.3 MeV, $\theta = 30°$. Unfortunately lack of sufficient running time and a shortage of suitable targets made it impossible to pursue the investigation of this reaction further at this time. The results which we shall describe must be considered to be of a preliminary nature.

We observe clearly the triton groups to the bound ground state and 3.36-MeV first excited state of $^{10}$C. We also observe the excitation of unbound states analogous to the 6-7 MeV states in $^{10}$Be, although we are not able to resolve the analogues of all of these six states. This is hardly surprising since two of the

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Table 1

Known[1]) Analogue T=1 States in the A=10 Triad

| $^{10}$Be | | | $^{10}$B | | | $^{10}$C | |
|---|---|---|---|---|---|---|---|
| | | | | | | Previous Work | This Work[e)] |
| $E_x$ (MeV ± keV) | $J^\pi$ | $\Gamma$ (keV) | $E_x$ (MeV ± keV) | $J^\pi$ | $\Gamma$ (keV) | $E_x$ (MeV ± keV) | |
| 0 | $0^+$ | a) | 1.740 ± 2 | $0^+$ | b) | 0 [d)] | 0 |
| 3.366 ± 3 | $2^+$ | b) | 5.166 ± 4 | $2^+$ | 0.003 | 3.360 ± 17[b)] | 3.37 ± 30 |
| 5.958 ± 5 | $2^+$ | b) | | | | 5.6 ± 100 | (5.03 ± 60)[f)] |
| 5.959 ± 5 | $1^-$ | b) | 7.479 ± 2 | $(2^-)$ | 72 | | 5.28 ± 60 |
| 6.178 ± 9 | $0^+$ | b) | 7.561 ± 1 | $0^+$ | 3.3 | | (5.60 ± 60)[f)] |
| 6.262 ± 9 | $2^-$ | b) | 7.77 ± 30 | $2^-$ | 210 | | 6.58 ± 60 |
| 7.377 ± 10 | $3^-$ | 16 | 8.892 ± 6 | $3^{(-)}$ | 84 | (7.2 ± 200) | |
| 7.548 ± 10 | $2^+$ | 6 | 8.896 ± 2 | $2^+$ | 36 | | |
| [c)] | | | [c)] | | | | |

a) $\tau_{1/2} = (2.7 \pm 0.4) \times 10^6$ years.

b) These states are sharp.

c) Higher excited states have also been observed.

d) $\tau_{1/2} = 19.41 \pm 0.04$ sec.

e) The 5 and 6-MeV levels listed below are not uniquely assigned corresponding analogue states in $^{10}$Be and $^{10}$B.

f) Assignment to $^{10}$C not certain: see text.



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Figure Captions

Fig. 1. Spectrum from the $^{6}Li(^{3}He,t)^{6}Be$ reaction at $E(^{3}He) = 39.4$ MeV, $\theta = 40°$. N represents the average number of counts in a two-channel wide window, at the corresponding average value of the abscissa channel. The $E_x$ scale gives the excitation energy in $^{6}Be$. The binding energies ($E_b$) for breakup into $^{4}He + 2p$, $^{5}Li + p$ and $2^{3}He$ are also shown.

Fig. 2. Sepctrum from the $^{10}B(^{3}He,t)^{10}C$ reaction at $E(^{3}He) = 30.6$ MeV, $\theta = 30°$. See also caption of Figure 1.

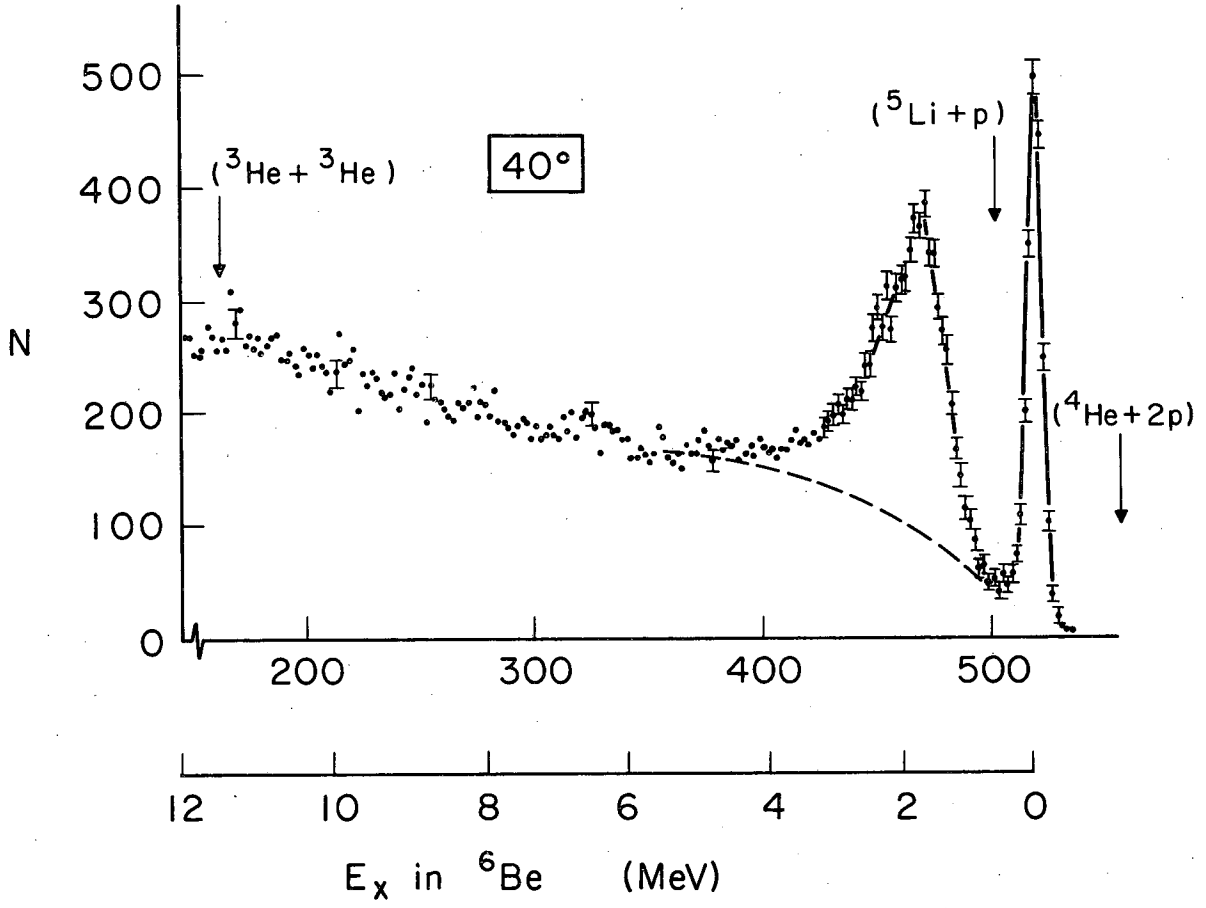
500
400
300
200
100
0
N
($^3$He + $^3$He)
40°
($^5$Li + p)
($^4$He + 2p)
200
300
400
500
12
10
8
6
4
2
0
$E_x$ in $^6$Be (MeV)
MUB-9348

Fig. 1

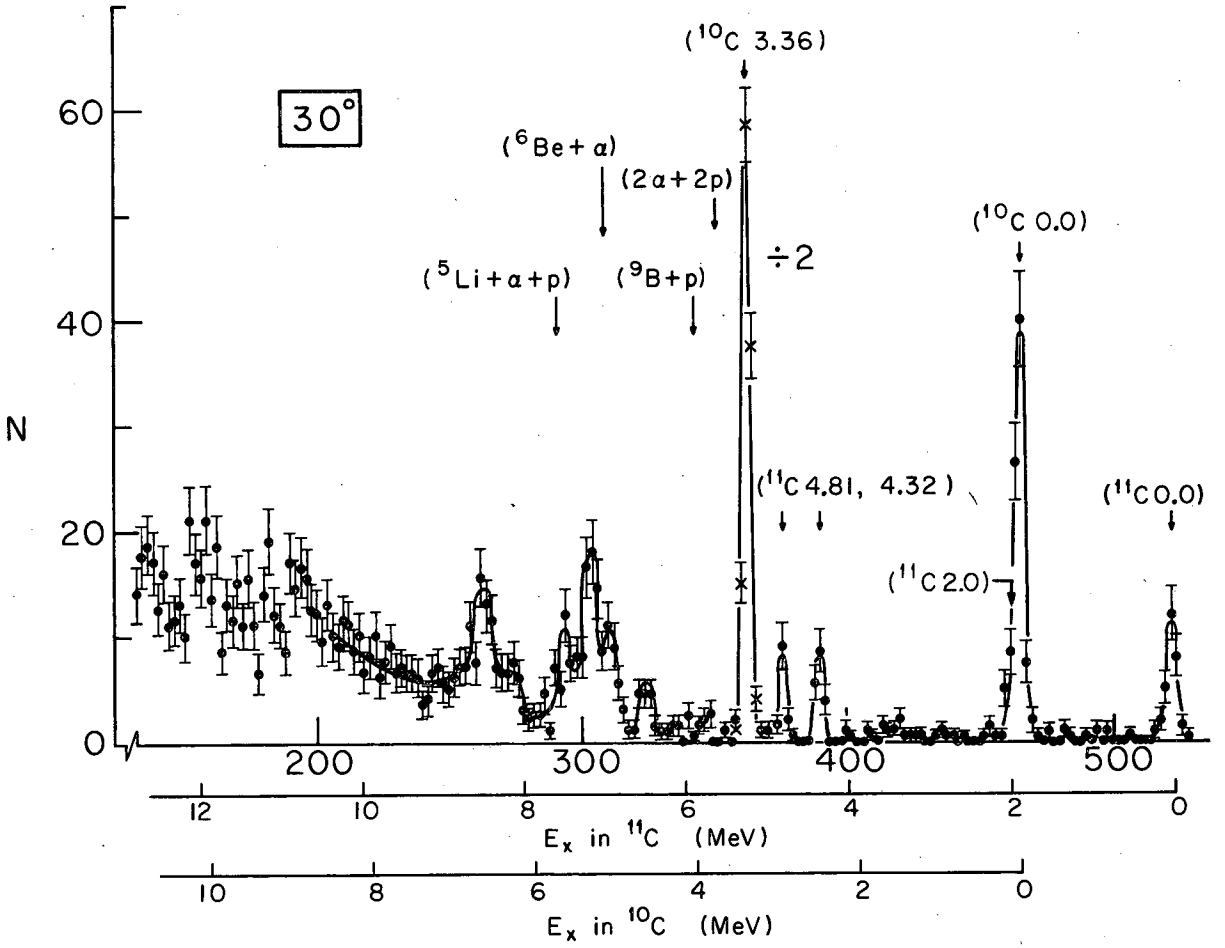
(10C 3.36)
30°
(6Be+α)
(2α+2p)
(5Li+α+p)
(9B+p)
÷2
(10C 0.0)
(11C 4.81, 4.32)
(11C 2.0)
(11C 0.0)
N
60
40
20
0
200
300
400
500
12
10
8
6
4
2
0
Ex in 11C (MeV)
10
8
6
4
2
0
Ex in 10C (MeV)
MUB-10259

Fig. 2