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INVESTIGATION OF THE (^{10}B,^{6}Li* (3^+, 2.18 MeV)) REACTION AS A METHOD FOR α-CLUSTER TRANSFER STUDIES*

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Abstract:

The four-nucleon transfer reaction $^{12}C(^{10}B,^{6}Li^*(2.18\ MeV))^{16}O$ has been studied at 68 MeV by coincidence measurement of the d+α breakup particles. The reaction is quite selective as is observed in other established α-transfer reactions.

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Considerable theoretical and experimental effort has been directed toward understanding particle clustering in nuclei [1,2]. Experimental investigations of α-like correlations in light nuclei have proceeded to a large extent via direct α-cluster transfer reactions. The reactions that have generally been studied until now have involved bound products, e.g., the $(^{6}Li,d)$ and $(^{7}Li,t)$ reactions. Similar α-transfer studies involving the unbound reaction product ^{8}Be, such as in the $(^{12}C,^{8}Be)$ reaction, have also been successfully utilized [3]. An additional interesting transfer reaction involving an unbound reaction product is that of $(^{10}B,\ ^{6}Li^{*}(3^{+},\ 2.18\ MeV))$. The possibility of studying this reaction has been suggested by Robson [4]. We describe here its initial study.

The potential suitability of the $(^{10}B,^{6}Li^{*}(2.18\ MeV))$ reaction for α-cluster transfer studies is suggested by investigations of four-nucleon pickup reactions on ^{10}B [5,6]. Such reactions indicate that the parentage coefficient for decomposition of ^{10}B into the $[\alpha + {}^{6}Li^{*}(2.18\ MeV)]$ state is much larger than that for decomposition into the $[\alpha + {}^{6}Li$ g.s.$]$ or other excited ^{6}Li configurations. Shell-model calculations are in qualitative agreement with this result [7,8]. Given the availability of sufficiently intense ^{10}B beams, the study of light nuclei via the $(^{10}B,^{6}Li^{*}(2.18\ MeV))$ reaction is quite feasible.

In order to observe the $^{6}Li^{*}(2.18$ MeV) state it is necessary to detect its decay products. Since the only breakup threshold below the $^{6}Li^{*}(2.18$ MeV) state is that of $d + \alpha$ lying 1.47 MeV above the ground state, the 2.18 MeV(3^{+}) state [9] (hereafter referred to as $^{6}Li^{*}$) will decay into this channel with a relative energy ε between the d and α fragments of 0.71 MeV. In the laboratory system the $^{6}Li^{*}$ decay products are confined to a cone centered around the $^{6}Li^{*}$ center-of-mass direction. The maximum opening angle for this cone is given by

$$\beta_{max} = 2 \sin^{-1} [(2\varepsilon/E)^{1/2}]$$

where $\varepsilon = 0.71$ MeV and E is the $^{6}Li^{*}$ laboratory energy. A reasonably efficient method for detecting the $d + \alpha$ products is to arrange two particle telescopes in a close vertical geometry (with respect to the scattering plane). This geometry is chosen so that the counter telescopes subtend a good portion of the $^{6}Li^{*}$ breakup cone and yet limit the kinematic broadening. Figure 1(a) presents a schematic representation of the detection system used in this work.

Each counter telescope consisted of a 200 μm ΔE, a 3mm E and a 400 μm reject counter (the last is not illustrated in Fig. 1(a)). The counter telescopes were collimated by 3mm wide and 10mm high slits which were separated by 10mm. At 11.5 cm distance from the target the horizontal acceptance angle of this system was 1.5°. The timing resolution between the two ΔE counters was approximately 1 ns. Fast pileup rejectors were employed to permit reasonable counting rates (1.5 X 10^4/s) in each ΔE counter. Particle-particle coincidence data were stored event by event on magnetic tape by a ModComp IV computer. Software particle identification was performed using a standard light-ion identification algorithm.

Observation of the (^{10}B,$^{6}Li^*$) reaction was accomplished by bombarding a carbon target (120 $\mu g/cm^2$) with a 68 MeV ^{10}B beam produced at the LBL 88-inch Cyclotron. $^{6}Li^*$ events were measured from 13° to 30° in the lab system over an energy range of 35-66 MeV. The efficiency for $^{6}Li^*$ detection as calculated by a Monte Carlo code is shown in fig. 1(b).

Although all light ($A \leqslant 4$) particle-particle coincidences were measured, $^{6}Li^*$ spectra were obtained by requiring d + α events in separate telescopes within 1.5 ns via software gating. The contribution of random events was determined by measurement of d,α coincidences between successive cyclotron beam bursts. A $^{12}C(^{10}B,^{6}Li^*)^{16}O$ energy spectrum taken at Θ_{lab} = 13° is shown in fig. 2. The resolution is $\sim$500 keV FWHM, which is primarily due to kinematic broadening.

Transitions to a number of levels in ^{16}O are evident in fig. 2. Provided the peaks observed are due to the population of single states, their excitation energies in ^{16}O are determined to be E_x = 0.00, 6.09, 6.91, 10.35, 11.12, 14.69, 16.21 and 20.88 MeV with a maximum uncertainty of $\pm$ 160 keV.

At $\Theta_{lab} = 13°$ the absolute differential cross sections (to within an estimated $\pm 30\%$) for these transitions are 12; 500; 170; 1000; 200; 1650; 2400 and 2000 μb/sr, respectively. The angular distributions for these transitions are forward peaked and fairly structureless. With the exception of the transition to the ground state, which decreases more slowly in strength with angle, the angular distributions decrease in magnitude by factors of 5-10 between 13° and 30° in the lab -- a feature consistent with a direct reaction mechanism.

Although the d-α coincidences observed are consistent with an excited ^{6}Li direct reaction product, whether these unbound products are predominantly of the ^{6}Li*(2.18 MeV) character must be established. Conceivably d + α coincidences could arise from the decay of higher lying levels of ^{6}Li($E_x \geqslant 4.31$ MeV). However, the probability for exciting such states via an α-transfer is reduced compared to producing the 3^+ (2.18 MeV) state due to the differences in α-spectroscopic factors [6,7]. The likelihood of observing highly excited ^{6}Li nuclei is further reduced due to their larger breakup cones, resulting in smaller detection efficiencies; the efficiency for detection of ^{6}Li* (4.31 MeV) d+α is a factor of 5-10 smaller than that for the similar decay of the 2.18 MeV level over the ^{6}Li* kinetic energies considered here.

This expectation that the $^{6}Li^{*}(2.18\ MeV) \rightarrow d+\alpha$ transition is the dominant process observed is verifiable experimentally. Nuclear reactions producing three final particles (here ^{16}O, d and α) have multi-valued kinematic solutions. Each allowable kinematic locus can be viewed by projecting it onto an energy axis such as E_d or E_α. Figure 3 shows a projected energy spectrum for transitions producing the $^{16}O(10.35\ MeV)$ state at $\Theta_{lab} = 20°$. Other projected energy spectra are similar to this one. It can be seen in fig. 3 that the α-particle energy clusters around two values. Each E_α corresponds to a definite d-α relative energy (ε) as indicated by the upper energy scale. Only transitions from the 2.18 MeV level in ^{6}Li ($\varepsilon = 0.71$ MeV) are evident. The dashed curve is a Monte Carlo prediction of the projected energy spectrum for $^{6}Li^{*}(2.18\ MeV) \rightarrow d+\alpha$ transitions <u>assuming</u> for simplicity an isotropic distribution of the d-α fragments in their common center-of-mass system. The good agreement with the data lends support to our conclusion that there are few d-α coincidence events arising from the decay of ^{6}Li levels above 2.18 MeV or interference from other processes such as sequential evaporation of an α and d from a compound nucleus.

The production of $^{6}Li^{*}$ via an α-cluster transfer is suggested by the similarity of ^{16}O levels populated in the (^{10}B,$^{6}Li^{*}$), (^{12}C,^{8}Be) and (^{7}Li,t) reactions [3,10-12].

In addition, the $^{12}C(^{10}B,^{6}Li)^{16}O$ reaction observed at 45 MeV [5], an example of a less selective four-nucleon transfer reaction, showed transitions to levels at 8.88, 9.85 and 13.26 MeV which were not evident in the $(^{10}B,^{6}Li^{*})$ reaction. In particular, the 2^- (8.88 MeV) state has unnatural parity and cannot be populated by a direct α-transfer on ^{12}C. (Our $(^{10}B,^{6}Li)$ data at 68 MeV are similar to those of ref. 5 at 45 MeV.)

Previous studies of ^{16}O have established the existence of two rotational bands, the 4p-4h, $K^{\pi} = 0^+$ band based on the 0^+(6.05 MeV) level and the $K^{\pi} = 0^-$ band based on the 1^-(9.63 MeV) state [13]. The peaks observed in the $^{12}C(^{10}B,^{6}Li^{*})^{16}O$ reaction at E_x = 6.09, 6.91, 10.35 and 16.21 MeV are consistent with transitions to members of the $K^{\pi} = 0^+$ band [0^+(6.05 MeV), 2^+(6.92 MeV), 4^+(10.35 MeV) and 6^+(16.29 MeV)], although population of other nearby states, such as the 3^-(6.13 MeV) and 1^-(7.12 MeV) levels, cannot be excluded due to the relatively poor experimental resolution. The peaks located at E_x = 14.69 and 20.88 MeV correspond closely to the excitation energies of the 5^-(14.67 MeV) and 7^-(20.88 MeV) members of the 0^- rotational band. As has been observed in other α-transfer studies [3,10,11], we do not find evidence for population of the 1^-(9.63 MeV) and 3^-(11.60 MeV) band members.

Two other peaks observed in this reaction correspond to the ground state and to a state at 11.12 MeV excitation energy. The weak intensity of the ground state transition is consistent with observations in other multiparticle transfer reactions [14] in which it is found that states with a collective character are excited preferentially over a spherical ground state. The weak transition to a state at 11.12 MeV is most likely to the 4^+(11.095 MeV) level and not to the unnatural-parity 3^+(11.08 MeV) state. The structure of this 4^+ state is complicated, however, as it is seen in two, three and four-nucleon transfer reactions [13].

In summary, the (^{10}B,^6Li*) reaction appears to be a potentially useful additional tool for investigating α-clustering in light nuclei. The relatively large ^6Li* production cross sections along with the absence of complications from higher ^6Li levels enhance the feasibility of this reaction. With the use of larger area position-sensitive detectors, it would be possible both to increase the ^6Li* detection efficiency and to improve the energy resolution.

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Figures Captions

Fig. 1. (a) Schematic diagram of the $^{6}Li^{*}$ detection system. (b) Efficiency curve for $^{6}Li^{*}$ detection. The effective solid angle is the solid angle of the detection system multiplied by the detection efficiency.

Fig. 2. Energy spectrum of the $^{12}C(^{10}B, ^{6}Li^{*}(2.18))^{16}O$ reaction at $\Theta_{lab} = 13°$ and $E_{^{10}B} = 68$ MeV. Excitation energies are given in MeV.

Fig. 3. Projected energy spectrum of d-α coincidences which resulted in the population of the $^{16}O(10.35$ MeV) state at $\Theta_{lab} = 20°$. The upper energy scale shows the relative energy between the d-α pair for each E_{α}. The Monte Carlo prediction assumes the $^{6}Li^{*}(2.18) \rightarrow d+\alpha$ transition.

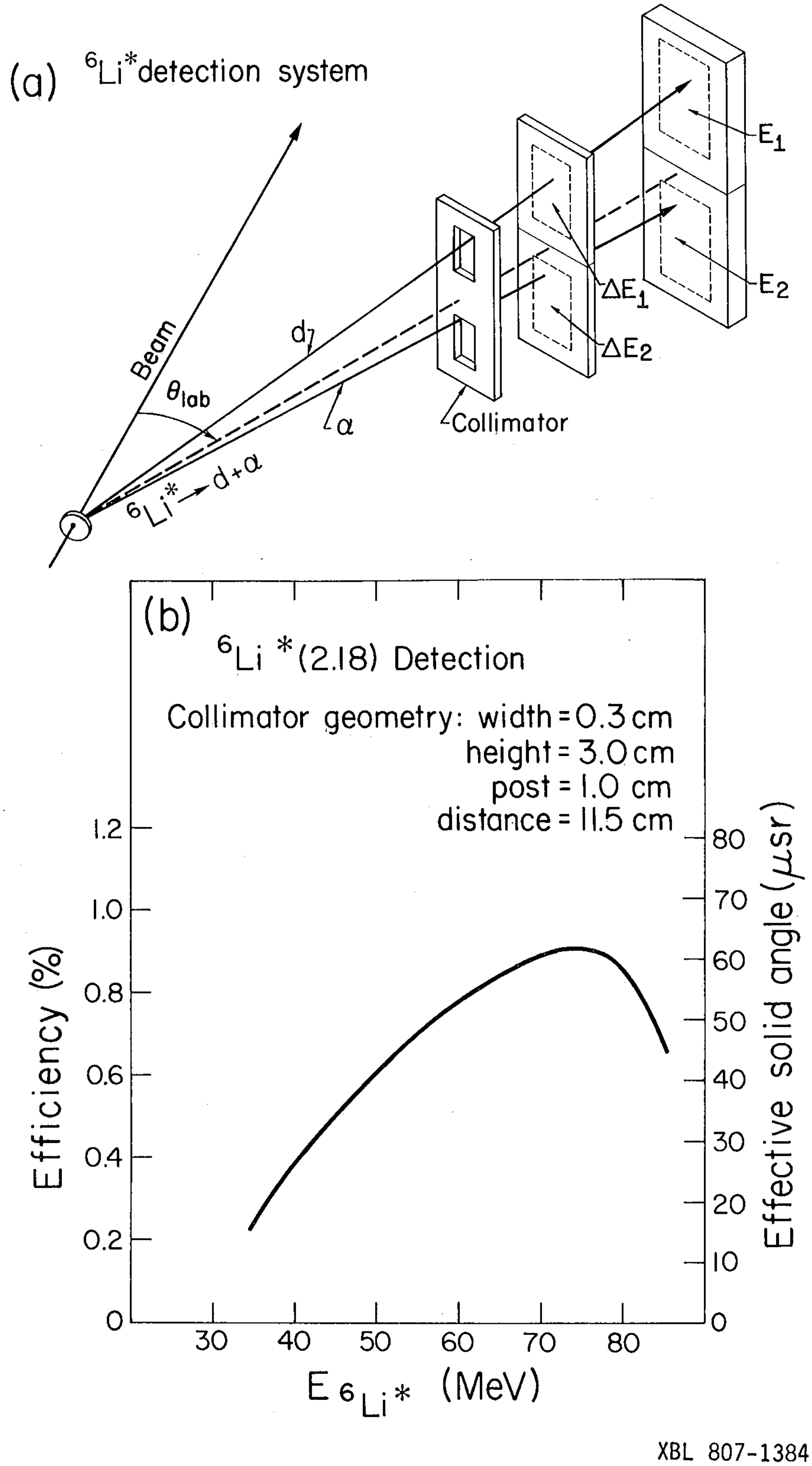
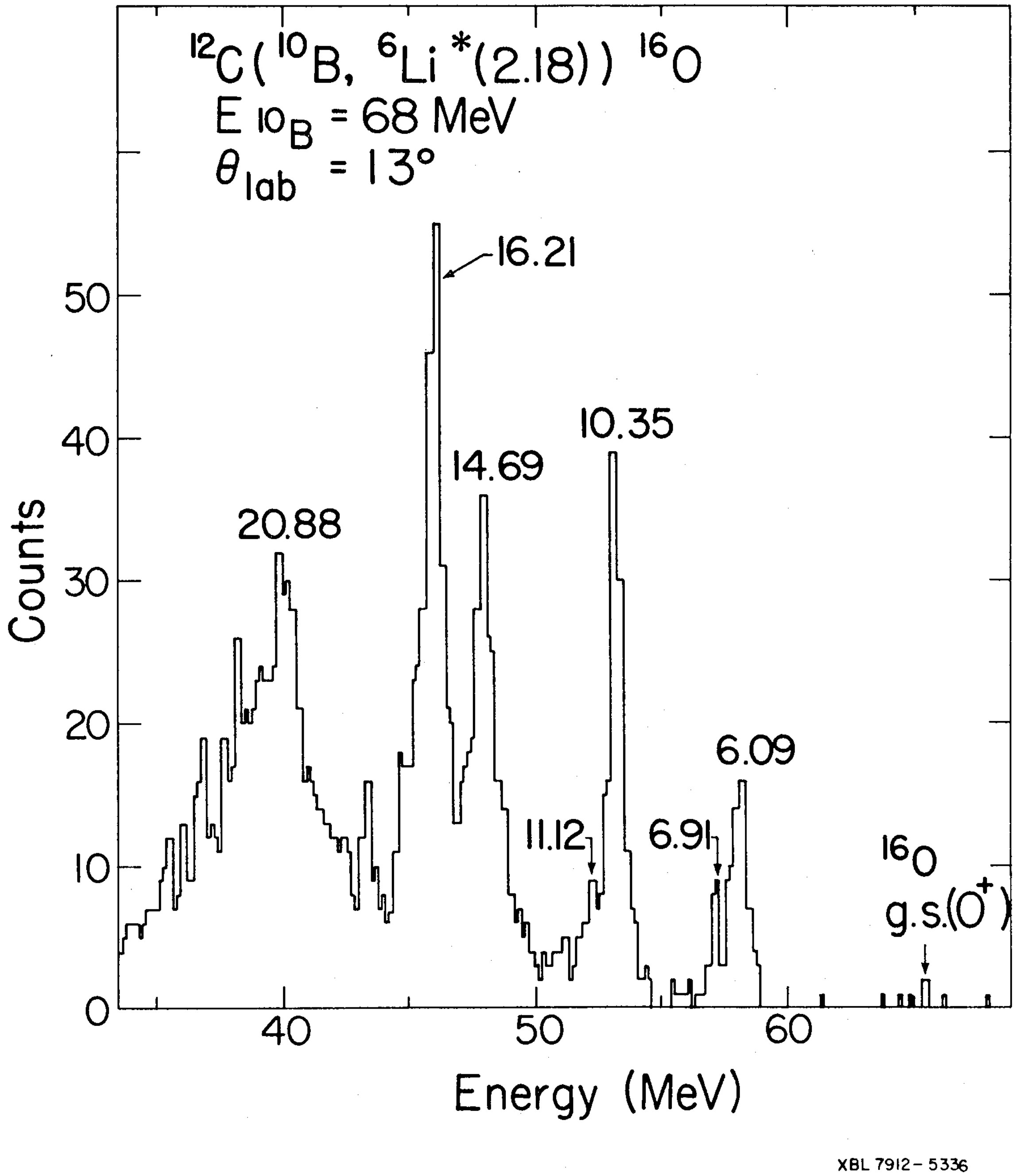
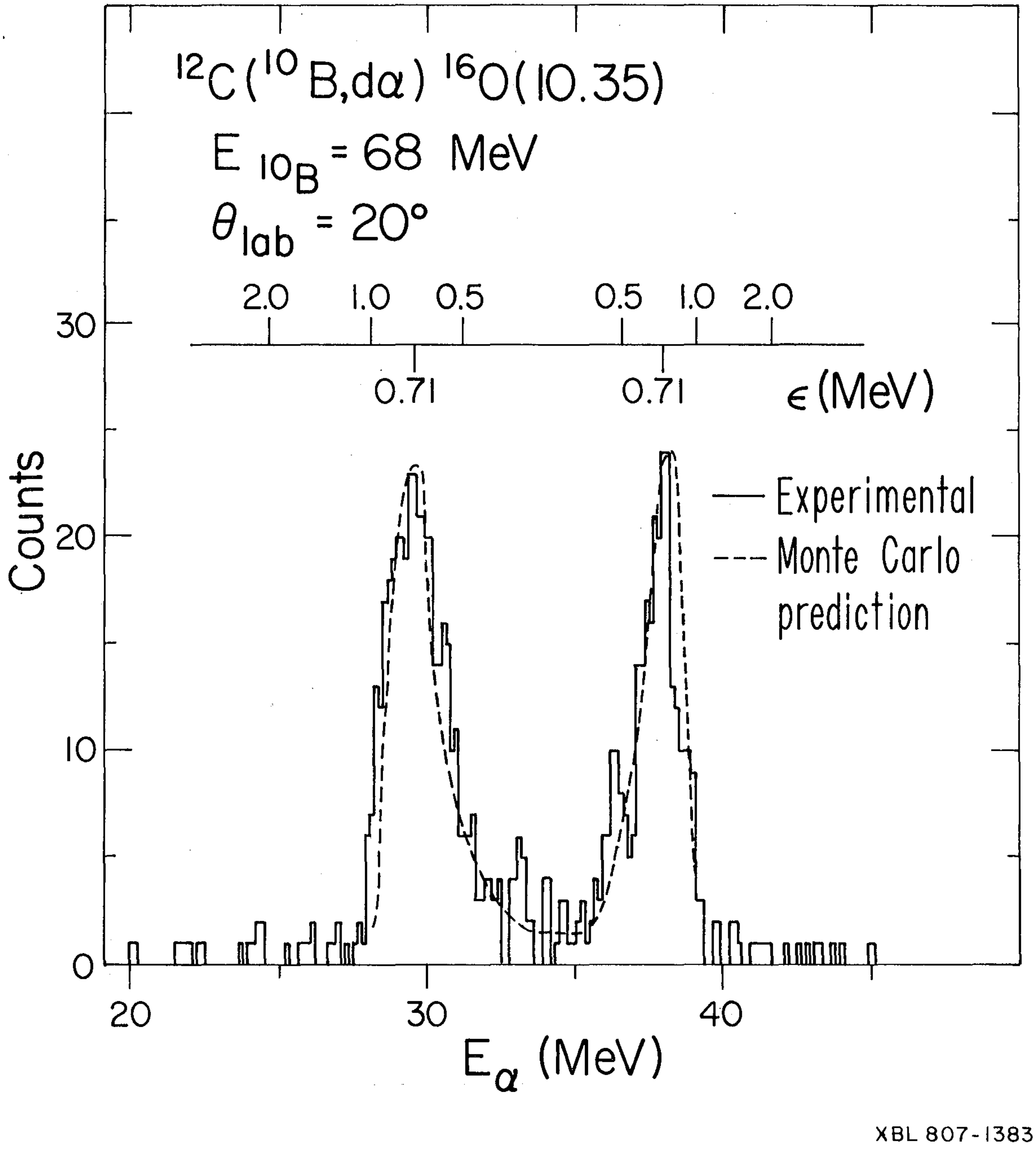

(a) ⁶Li*detection system
Beam
θlab
d
α
⁶Li* → d+α
Collimator
ΔE1
ΔE2
E1
E2
(b)
⁶Li *(2.18) Detection
Collimator geometry: width = 0.3 cm
height = 3.0 cm
post = 1.0 cm
distance = 11.5 cm
Efficiency (%)
Effective solid angle (μsr)
E ⁶Li* (MeV)
0
0.2
0.4
0.6
0.8
1.0
1.2
10
20
30
40
50
60
70
80
XBL 807-1384

Fig. 1



$^{12}C(^{10}B, ^{6}Li^{*}(2.18))\ ^{16}O$
$E_{^{10}B}$ = 68 MeV
θ_{lab} = 13°
16.21
14.69
10.35
20.88
11.12
6.91
6.09
^{16}O g.s.(0^{+})
Counts
0
10
20
30
40
50
40
50
60
Energy (MeV)
XBL 7912-5336

Fig. 2



$^{12}C(^{10}B,d\alpha)\,^{16}O(10.35)$
$E_{^{10}B} = 68$ MeV
$\theta_{lab} = 20°$
2.0 1.0 0.5 0.5 1.0 2.0
0.71 0.71
ϵ (MeV)
— Experimental
--- Monte Carlo prediction
Counts
0 10 20 30
20 30 40
E_α (MeV)
XBL 807-1383

Fig. 3