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Publication Date
1976-06-01

Submitted to Physical Review Letters

LBL-5038
Preprint c.1

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June 24, 1976

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

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THE (α, ^{2}He) REACTION AS A SPECTROSCOPIC TOOL FOR INVESTIGATING HIGH SPIN STATES*

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June 1976

Abstract:

A ^{2}He detection system has been developed and used to investigate the (α, ^{2}He) reaction at 65 MeV on ^{12}C, ^{13}C, and ^{16}O targets. Extreme spectroscopic selectivity with preferential population of final states with $(d_{5/2})^2_{4+}$ character was observed. Applications of this experimental technique to the detection of other unbound reaction products are proposed.

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Experimental systems capable of detecting nuclear reaction products in resonant final states with good efficiency and energy resolution can open up a wide range of unexplored nuclear reactions. Although at present such studies are largely confined to the detection of ^{8}Be nuclei,[1,2] Robson[3] has pointed out many other interesting resonant systems which can be detected as reaction products. Additionally, the well known final state interaction in the two-nucleon $^1S_0$, T = 1 system can be utilized; in particular, this interaction in the ^{2}He system localizes the two breakup protons into a narrow cone. Thus ^{2}He can readily be detected with two proton detectors arranged in an appropriate geometry, and a few results on single neutron transfer via the (^{3}He, ^{2}He) reaction have been reported.[4,5]

A very interesting reaction which can be studied at reasonably high bombarding energies with such a detection system is that of (α,^{2}He), potentially a direct 2n transfer reaction very similar to the direct np-transfer reaction (α,d). The demonstrated selectivity of the (α,d) reaction[6,7,8] makes it a valuable spectroscopic tool with which to investigate high spin states in nuclei with $T_z = T_z$ (target), and therefore one can anticipate that the (α,^{2}He) reaction might selectively populate high spin states in nuclei with $T_z = T_z$ (target) + 1. This reaction is particularly appealing due to the unavailability of high energy triton beams, so that the analogous (t,p) reaction has not been investigated under conditions which favor large angular momentum transfer -- nor have more than a few 2n transfer reactions induced by heavy ions been reported (cf. ref. 9). We report here the results of this initial observation of the (α,^{2}He) reaction on ^{12}C, ^{13}C and ^{16}O targets induced by 65 MeV α-particles from the Lawrence Berkeley Laboratory 88-inch cyclotron. These data establish the expected high selectivity of this reaction and its usefulness as an important spectroscopic tool.

Although detection of the two protons from in-flight breakup of ^{2}He is similar to detecting ^{8}Be decay via its two α-particles, a difference arises in that the disintegration energy of ^{2}He does not originate from the breakup of a narrow state as is the case for ^{8}Be, but is rather a distribution described by the Watson-Migdal formalism.[10] In our initial design for a ^{2}He detector, we assumed for simplicity that the breakup energy of the ^{2}He system was given by the "average" value of this distribution (400 keV).

The two protons arising from the breakup of ^{2}He are emitted into a cone in the laboratory, which is defined by the center of mass energy of the ^{2}He system and by its breakup energy. In order to achieve good detection efficiency, the acceptance angle of the two coincident proton telescopes has to be similar to the size of the breakup cone, which is approximately 15° for 40 MeV ^{2}He events. On the other hand, energy resolution considerations require a small angular acceptance to minimize kinematic broadening. An excellent compromise between efficiency and energy resolution is obtained by arranging the two proton telescopes vertically, thus achieving relatively good efficiency due to the large vertical acceptance angle, and reasonably good energy resolution by limiting the horizontal acceptance angle.

Figure 1(a) shows the ^{2}He detection system, consisting of two ΔE-E counter telescopes. The ΔE detectors were phosphorus-diffused Si, 380 μm thick and the E detectors were Si(Li), 5 mm thick, all having the same area of 1×1.4 cm^{2}. Two collimator slits separated by a post were employed, so that the system subtended a 15° vertical and a 4° horizontal acceptance angle. ^{2}He events were identified by using standard particle identification techniques as well as subnanosecond fast timing between the two ΔE counters, which drastically reduced random events. In addition, fast pileup rejection was utilized so that high singles counting rates (30 kHz) could be tolerated in the ΔE counters.

Figure 1(b) shows the relative time distribution of observed proton coincidences from the reaction $^{13}C(\alpha,{}^{2}He)^{15}C$ at 13° lab angle. The observed FWHM (1.1 ns) of the distribution of flight time differences for the two protons agrees with predictions based on the assumption of 400 keV breakup energy (random coincidences from a single beam burst would have spanned up to 12 ns FWHM). The coincidence counting rate was measured at different geometries obtained by varying the distance between the target and the collimator. Figure 1(c) depicts the relative experimental efficiency versus the calculated efficiency[11] for three different ^{2}He energies at three distances. The experimental data, normalized at 10 cm, are well reproduced by the calculations. The agreement between the calculated and experimental relative efficiencies and the narrow ΔTOF peak require that the majority of the detected pp coincidences come from the breakup of the unbound ^{2}He system.

Representative spectra from the $(\alpha,{}^{2}He)$ reaction on ^{12}C, ^{13}C (90% enriched), and ^{16}O (as SiO_2) at forward angles are presented in Fig. 2. The experimental energy resolution of 350 keV was principally determined by kinematic broadening due to the 4° acceptance angle. As can be seen in the spectra, the $(\alpha,{}^{2}He)$ reaction is extremely selective; only very few states in the residual nuclei are populated. In ^{14}C strong transitions were observed to a 3^- level at 6.73 MeV and to a 4^+ level at 10.55 MeV with weaker transitions to the ground state and to a level at 14.67 MeV. The ^{15}C spectrum shows only strong transitions to the $5/2^+$ level at 0.74 MeV and to two states at 6.85 MeV and 7.35 MeV excitation energy, while in ^{18}O only population of the 4^+ level at 3.55 MeV was observed (weak transitions would be obscured due to the reactions on the Si in the target).

Preferential population of high spin states has been observed in the (α,d) reaction induced by 40-53 MeV α-particles on many light nuclei;[6,7,8] the selectively populated levels (e.g., of $(d_{5/2})^2_{5^+}$ or $(f_{7/2})^2_{7^+}$ character) correspond to particular kinematically favored transitions in which the np pair can be simply captured in a relative triplet state about an undisturbed target core. Since similar kinematic behavior and Q-values occur in the $(\alpha,{}^{2}He)$ reaction, one also expects to observe predominantly high spin states, but now those in which the nn pair is captured in a relative singlet state. At 65 MeV bombarding energy, the transferred angular momentum in a surface interaction on these targets is about 4-5 $\hbar$ and thus transitions to levels formed by capturing the two stripped neutrons into d-orbitals with configurations of $(d_{5/2})^2_{4^+}$ should be enhanced.[6] The observed strong population of the 4^+ states in ^{14}C (at 10.55 MeV) and in ^{18}O

(at 3.55 MeV), which have substantial $(d_{5/2})^2_{4^+}$ character,[12,13,14] is in agreement with this simple picture. Equally dominant transitions to states with possible configurations involving f-orbitals such as $(d_{5/2}\ f_{7/2})_{5^-}$ or $(f_{7/2})^2_{6^+}$ are expected and appear in reactions on targets in the 2s-1d shell[11] but will not be discussed here.

Noting Fig. 2(a), except for the weak population of the ^{14}C ground state, transitions to the other observed states in ^{14}C can be explained as kinematically favored transitions to S=0 components in the known 6.73 MeV $(d_{5/2}\ p_{1/2})_{3^-}$ state[12] and in the 14.67 MeV state (possibly 4^+ [9] of $(d_{5/2}\ d_{3/2})_{4^+}$ character[12] though without additional calculations $(d_{5/2}\ f_{7/2})_{5^-}$ cannot be excluded).[15]

Figure 3 shows angular distributions of the $^{12}C(\alpha,{}^2He)^{14}C$ transitions. As in the (α,d) results,[6,7] transitions to all the strongly populated levels show angular distributions which are relatively structureless and forward peaked; also, as before, the weaker transitions (here to the ^{14}C g.s.) show oscillatory behavior. The overall cross section is $\sim$100 times smaller than that observed in the (α,d) reaction, which is comparable to the difference observed between nn and np transfer in heavy ion reactions[9] - - though not necessarily of the same origin.[11]

Since the ^{12}C and ^{13}C targets only differ by a $p_{1/2}$ neutron, one expects the $(\alpha,{}^2He)$ reaction on ^{13}C to populate preferentially the same two-neutron configurations originally observed in reactions on ^{12}C, but now coupled to the $1/2^-$ target core. Thus the states observed in the ^{14}C spectrum should be split into two components in the ^{15}C spectrum, as has been observed in the analogous (α,d) reactions on ^{12}C and ^{13}C. Noting Fig. 2(b), then the doublet observed at 6.85 MeV - 7.35 MeV in ^{15}C can be interpreted as having a configuration $[\{^{12}C(0^+)p_{1/2}\}_{1/2^-} \otimes (d_{5/2})^2_{4^+}]_{7/2^-,9/2^-}$. Although this model does not predict the assignment of spins to the two components of the split state, relative enhancement via the (2J+1) statistical factor implies that the 7.35 MeV level might have the higher spin ($9/2^-$) because of its larger cross section. States at these excitation energies in ^{15}C have been observed in other reactions,[16] but definite spin assignments have not been reported. Since the $5/2^+$ state at 0.74 MeV has a configuration $[\{^{12}C(0^+)p_{1/2}\}_{1/2^-} \otimes p_{1/2}d_{5/2}]_{5/2^+}$, the $p_{1/2}$ neutron of ^{13}C and the transferred $p_{1/2}$ neutron must couple to spin 0 and no splitting can arise. These three $^{13}C(\alpha,{}^2He)^{15}C$ transitions and the $^{16}O(\alpha,{}^2He)^{18}O$ transiton to the 3.55 MeV $(d_{5/2})^2_{4^+}$ state all show forward peaked, structureless angular distributions. In addition, the observed cross sections of the transitions to the known 4^+ state in ^{14}C (10.55 MeV), to the sum of the split states in ^{15}C, and to the 4^+ state in ^{18}O are all equal within errors, which is further evidence for the assumption of a common $(d_{5/2})^2_{4^+}$ configuration for these states.

These results clearly demonstrate the utility of the $(\alpha,{}^2He)$ reaction as a new spectroscopic tool capable of locating many unobserved two-neutron states of high spin in the 2s-1d and higher shells. Furthermore, extension of this approach toward studying resonant final systems as reaction products to other cases seems particularly practical and fruitful. As will be reported elsewhere,[17] the present ^2He detection system simultaneously observes (at comparable yields) transitions of the α-particle to its 0^+ first excited state (α^*) at 20.1 MeV (observed via its p+t decay products). In addition, though only observed in low yield with this system, the study of transitions to the 16.7 MeV excited state of ^5He ($^5He^* \rightarrow$ d+t) would be readily permitted with minor geometric modifications. As one example, future studies of single and two neutron pickup via such unusual spectroscopic probes as $(^3He,\alpha^*)$ and $(^3He,{}^5He^*)$, respectively, might provide new insights into our knowledge of nuclear reaction mechanisms.

We would like to thank J. Walton for fabricating the large area detectors.

FOOTNOTES AND REFERENCES

*Work performed under the auspices of the U.S. Energy Research and Development Administration.

†On leave from: Institut für Strahlen-und Kernphysik der Universität Bonn, Germany. Supported by: Deutscher Akademischer Austauschdienst.

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FIGURE CAPTIONS

Fig. 1. (a) Schematic diagram of the ^{2}He detection system.

(b) Spectrum of the time-of-flight difference, ΔTOF, between the two breakup protons

(c) Comparison of experimental (dots) and theoretical (solid lines) ^{2}He detection efficiencies as a function of the distance between target and collimator. The experimental efficiencies have been normalized to the calculations at a distance of 10 cm.

Fig. 2. ^{2}He energy spectra obtained from the reactions (a) $^{12}C(\alpha,{}^{2}He)^{14}C$, (b) $^{13}C(\alpha,{}^{2}He)^{15}C$ and (c) $^{16}O(\alpha,{}^{2}He)^{18}O$ at an α-particle energy of 65 MeV.

Fig. 3. Absolute differential cross sections for the reaction $^{12}C(\alpha,{}^{2}He)^{14}C$ at 65 MeV. Statistical error bars are shown. The solid curves are meant to guide the eye.

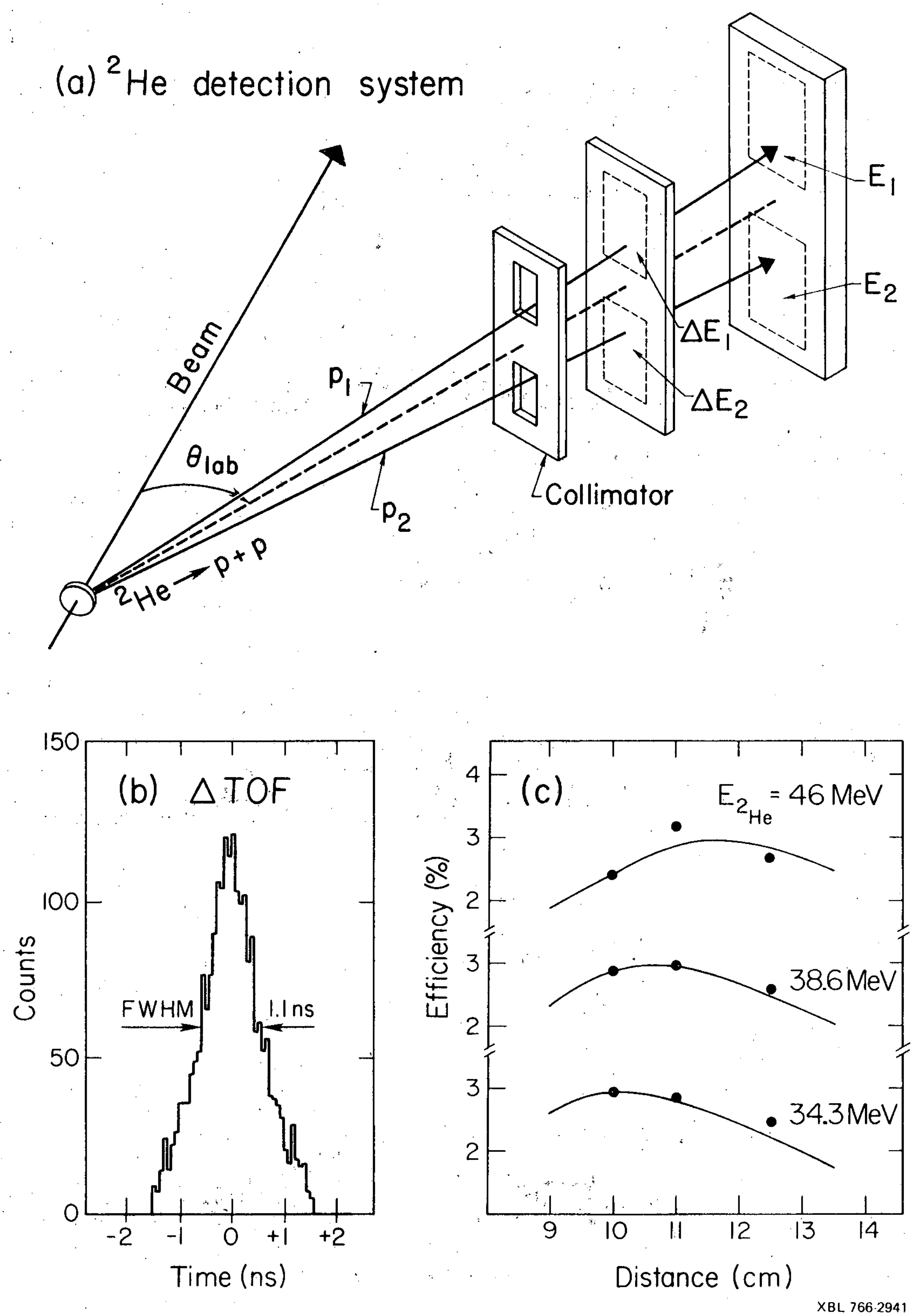

(a) ²He detection system
Beam
θ_{lab}
p_1
p_2
²He → p + p
Collimator
ΔE₁
ΔE₂
E₁
E₂
(b) ΔTOF
Counts
FWHM
1.1 ns
Time (ns)
(c)
$E_{^2He}$ = 46 MeV
38.6 MeV
34.3 MeV
Efficiency (%)
Distance (cm)
XBL 766-2941

Fig. 1

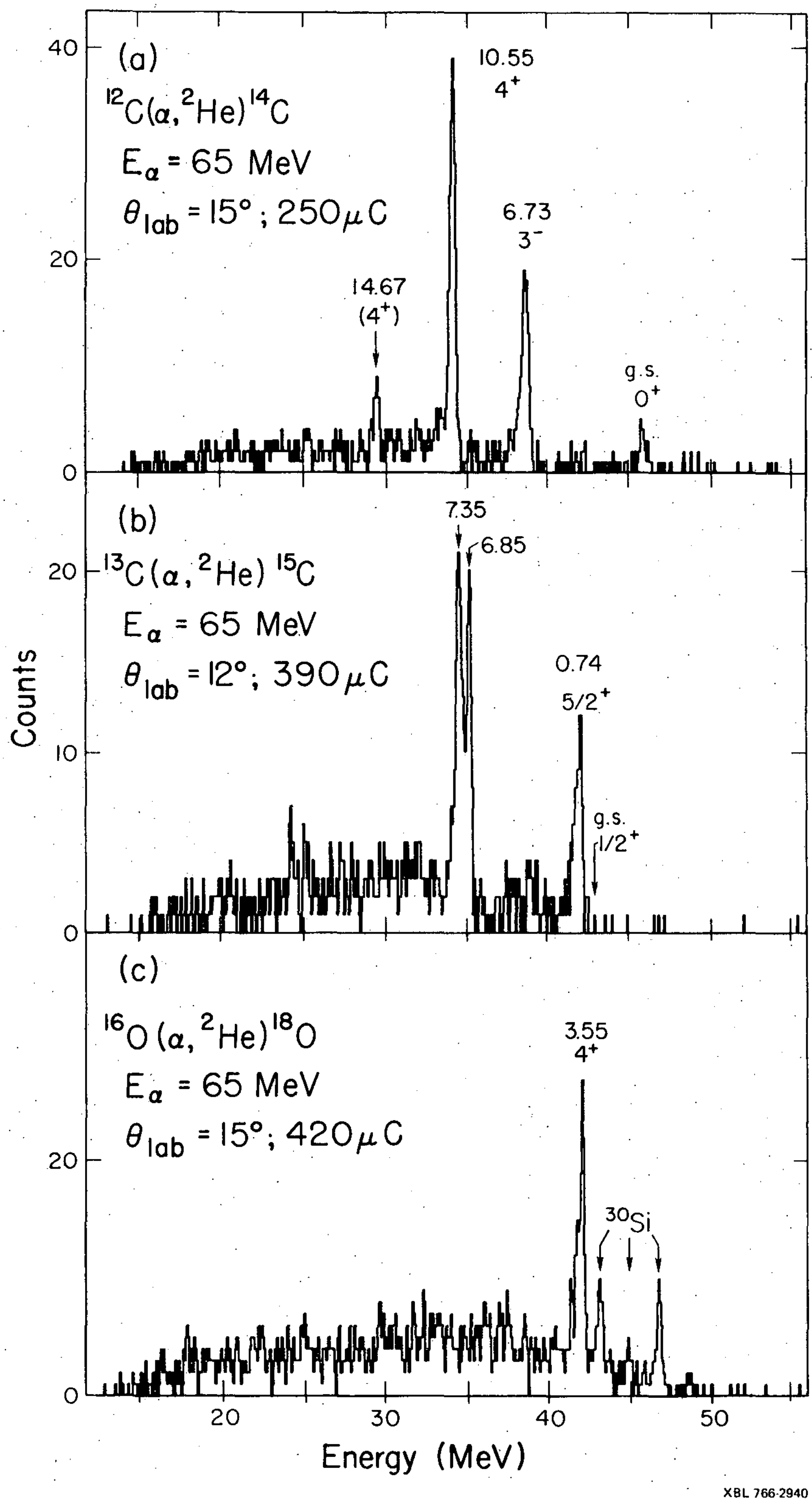
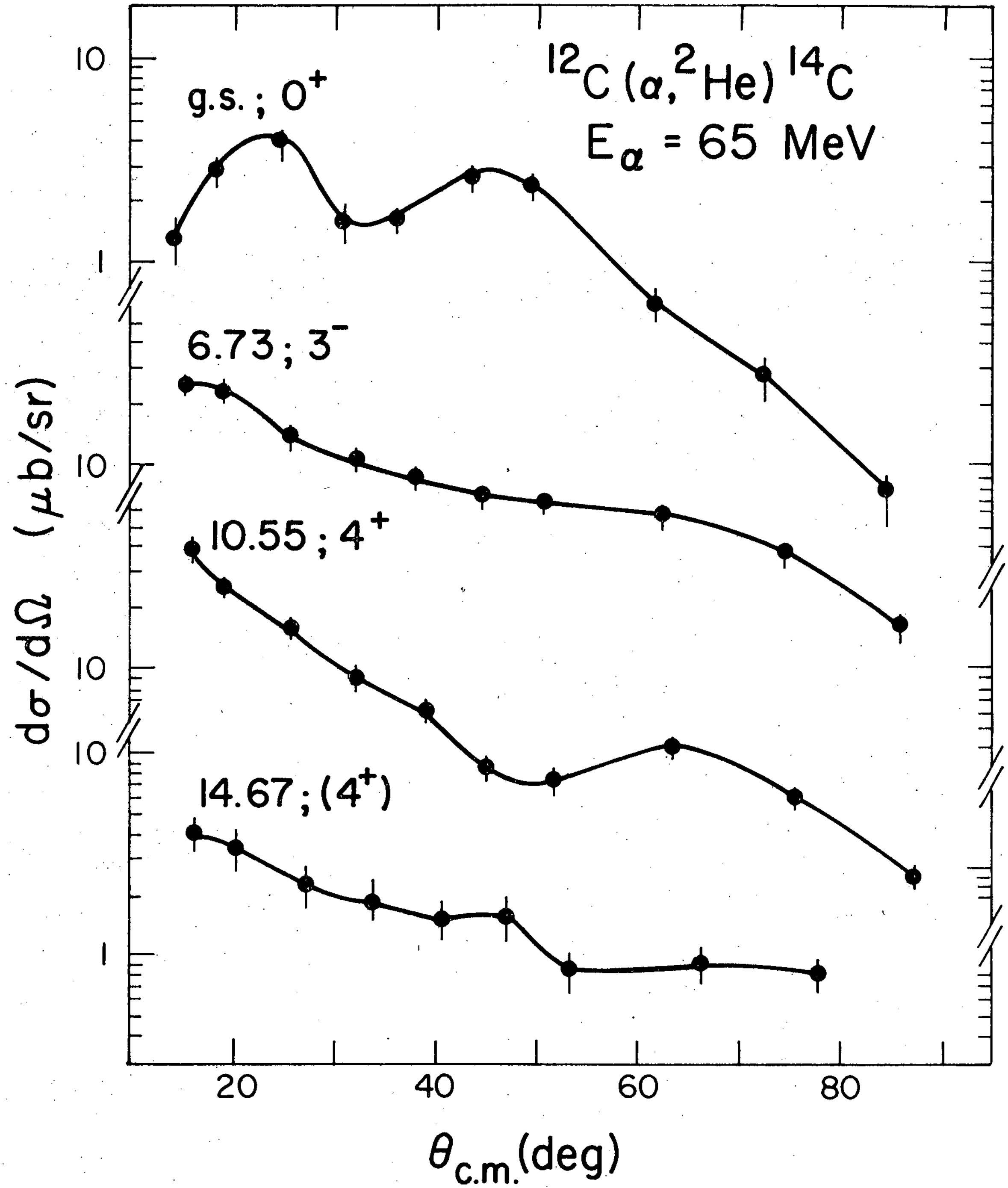

(a)
$^{12}C(\alpha,{}^2He)^{14}C$
E_α = 65 MeV
θ_{lab} = 15°; 250μC
10.55
4+
6.73
3−
14.67
(4+)
g.s.
0+
(b)
$^{13}C(\alpha,{}^2He)^{15}C$
E_α = 65 MeV
θ_{lab} = 12°; 390μC
7.35
6.85
0.74
5/2+
g.s.
1/2+
(c)
$^{16}O(\alpha,{}^2He)^{18}O$
E_α = 65 MeV
θ_{lab} = 15°; 420μC
3.55
4+
30Si
Counts
Energy (MeV)
XBL 766-2940

Fig. 2



XBL 764-2817

Fig. 3

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