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HIGH-SPIN ASSIGNMENTS IN THE 1p-SHELL UTILIZING THE J-DEPENDENT (p,α) REACTION*

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Abstract:

Direct (p,α) pickup reactions within the 1p-shell induced by 43.7 to 54.1 MeV protons are shown to possess angular distributions with characteristic behavior for J=1/2, 3/2, 5/2, and 7/2 transitions. This behavior is qualitatively reproduced by DWBA calculations and permits spectroscopic assignments of $J^{\pi}=7/2^{-}$ for both the 6.97 MeV state in ^{9}B and the 12.13 MeV state in ^{13}N.

Almost all previously reported (p,α) investigations below A=60 have been restricted to measurements of the ground state and a few low-lying excited states. As such the question of whether this pickup reaction, operating through its transferred angular momentum selection rule $\vec{J}=\vec{L}+\vec{1}/2$, is useful as a spectroscopic tool in the lighter nuclei remains largely unanswered. We have studied the (p,α) reaction induced by 43.7 to 54.1 MeV protons on ^{12}C, ^{13}C, ^{14}N, ^{15}N, and ^{16}O, observing transitions to levels in the residual nuclei ranging from the ground state to 15 to 22 MeV in excitation. These data show that, in fact, a strong and consistent J-dependence, in accord with the above selection rule, is observed for both L=1 and L=3 transitions, permitting (within the scope of this paper) two definite spectroscopic assignments. J-dependent effects (first reported by Lee and Schiffer[1] for (d,p) reactions) have previously been noted for L=1 (p,α) transitions on medium mass nuclei (see, e.g., Ref. 2, 3). Although a J-dependence for L=3 transitions in both (p,α) reactions[3] and (α,p) reactions[4] has been predicted from distorted-wave Born approximation (DWBA) calculations, no definite experimental evidence for this has hitherto been reported.

These (p,α) reactions were investigated using the proton beam of the Berkeley 88-inch spiral-ridge cyclotron at energies of 43.7 MeV on the ^{13}C, ^{14}N, and ^{15}N targets; 50.5 MeV on the ^{13}C target; and 54.1 MeV on the ^{12}C and ^{16}O targets. The experimental details have been described previously.[5] Alpha particles from the reaction were identified by a Goulding-Landis particle identifier. Gas targets of $^{16}O_2$, $^{15}N_2$ (enriched to 99%), $^{14}N_2$, and $^{13}CH_4$ (enriched to 93%) and a solid ^{12}C target were used. Representative spectra of the $^{12}C(p,\alpha)^9B$ and $^{16}O(p,\alpha)^{13}N$ reactions, with experimental resolutions of approximately 150 and 190 keV, respectively, are shown in Figs. 1 and 2. Transitions examined in all the residual nuclei yielded angular distributions, taken between approximately 10° and 80° center-of-mass (c.m.), on about 50 levels.

This report will cover, with one exception, only those transitions for which a unique value for L and J is required by the selection rules. A detailed analysis of our results as well as a comprehensive discussion of the direct pickup character of these (p,α) reactions (at forward angles and at our bombarding energies) will be presented in a subsequent publication. A strong indication of a dominant pickup mechanism would be the highly selective population of "pure" p-shell final states[6] in all the residual nuclei. Such an effect was indeed observed. The strongest (p,α) transitions consistently populated only p-shell levels in the final nuclei with cross-sections which were larger, by usually one or two orders of magnitude, than those to non-p-shell levels. In contrast to this, a knockout mechanism, for example, would have permitted some transitions to both types of levels, perhaps most strongly for reactions on the ^{12}C and ^{16}O targets (it would permit the incident proton to be captured into either the 1p or (2s,1d) shell). The spectrum in Fig. 2 particularly illustrates the differing relative cross-sections for transitions to p-shell and non-p-shell final states.

Angular momentum selection rules restrict (p,α) transitions between p-shell levels to L=1 (with J=1/2 or 3/2) or L=3 (with J=5/2 or 7/2). Figure 3 shows some (p,α) angular distributions for which L=1. While all the distributions peak toward zero degrees, there is little additional similarity between the J=1/2 and 3/2 distributions. However, the uniformity and consistency of the angular distributions for a given J are pronounced. It is noteworthy that this uniformity persists even with differing kinematic effects and is generally preserved over a range of almost 18 MeV of excitation in the $^{15}N(p,\alpha)^{12}C$ reaction.

Transitions in which L=3 are shown[7] in Fig. 4. The only consistent feature (an L-dependent effect) appearing in these distributions is that the first maximum no longer peaks toward zero degrees. The J-dependent effects are again apparent in the J=5/2 and 7/2 distributions, although the differences are not as pronounced as in the previous L=1 case. Although only one transition populated in these reactions was restricted solely to a J=5/2 transfer (the $^{16}O(p,\alpha)^{13}N$ [7.39 MeV, $5/2^-$] transition), at least four other transitions were observed to proceed predominantly through this mode.[8] One example of these is the $^{15}N(p,\alpha)^{12}C$ [16.1 MeV, 2+, T=1] transition. Simple spectroscopic arguments (employing in part the wave functions of Ref. 6) indicate that this transition should have a strong component of L=3, J=5/2 transfer, although L=1, J=3/2 transfer is also allowed. Since the angular distribution for this reaction (Fig. 4a) shows no obvious L=1 character at forward angles, it can be taken as a further example of an essentially pure J=5/2 transition. Of the final states populated in the J=7/2 transitions, only the $^{12}C(4+)$ and $^{10}B(4+)$ were previously known (the small angle behavior of the transition to the ^{10}B state is well accounted for by a small admixture of an L=1 component to an incompletely resolved neighboring level). The two remaining J=7/2 transitions will be discussed below. The angular distributions of the strong transitions to all the other p-shell states are consistent with these four different J-dependent shapes, either singly or in an appropriate combination.

Distorted wave calculations were employed to determine whether the observed J-dependence was consistent, at least in general, with simple theory. Since the initial aim was only for a qualitative comparison, a local, zero-range calculation, using the point-triton approximation, was carried out using the code DWUCK.[9] Figure 5 shows the results of these calculations for the $^{16}O(p,\alpha)^{13}N$ transitions to final levels with $J^{\pi}=1/2^-$, $3/2^-$, $5/2^-$, and $7/2^-$. The first three levels are well-known (see Ref. 5) and the last is discussed below. Optical model parameters for the proton channel, including a spin-orbit term, were obtained from Fricke, et al.[10] Parameters for the α-channel were obtained by refitting elastic α-scattering data[11] to correspond to a deeper and more realistic real well potential (V_o=175 MeV). The bound state radius and diffuseness were obtained from the analysis of ^3He scattering on ^{12}C as reported in

Ref. 5. In general the DWBA fits shown in Fig. 5 qualitatively reproduce the shapes of the distributions and hence clearly predict the observed J-dependence. The relatively slight dependence of the distributions on kinematic effects was also reproduced by the calculations.

Finally, this observed J-dependence permits us to make two definite spectroscopic assignments. The first of these is for the second strongest transition observed in the $^{12}C(p,\alpha)^{9}B$ reaction, which was to a level at 6.97 ± 0.06 MeV (see Fig. 1). This level, which has a width of approximately 2 MeV, accurately follows the kinematics of other ^{9}B levels and its excitation is consistent with a known $7/2^-$ state[12] in the mirror nucleus ^{9}Be at 6.6 MeV. The excitation of the 6.97 MeV level also corresponds well to a state reported at 7.1 ± 0.2 MeV in ^{9}B which was tentatively assigned[12] as $7/2^-$. Similarly, the third strongest transition in the $^{16}O(p,\alpha)^{13}N$ reaction was to a broad, hitherto unobserved, level ($\Gamma_{c.m.} \sim 300$ keV) at 12.13 ± 0.06 MeV (see Fig. 2). The excitation energy of this state corresponds favorably with that of a state at 12.42 MeV in its mirror nucleus ^{13}C which has $J^{\pi}=7/2^-$ (Ref. 5). The angular distributions for these (p,α) reactions to the ^{9}B and ^{13}N states, shown in Fig. 4b, are in agreement both with each other and with the known J=7/2 transition shapes. Both distributions are also consistent only with the DWBA predictions for J=7/2 (the prediction for the ^{13}N 12.13 MeV transition is shown in Fig. 5). Since these transitions proceed from 0+ targets, unique $J^{\pi}=7/2^-$ assignments are possible.

In conclusion, the high selectivity exhibited by these (p,α) reactions leaves little doubt as to the dominance of the direct pickup mechanism at these energies and at forward angles. The evidence for a strong J (and L) dependence is equally apparent. The angular distributions exhibit a dependence on J which is both consistent and uniform and, to first order, appears independent of any kinematic effects. Simple DWBA calculations appear capable of reproducing the qualitative features of the observed distributions. The spectroscopic utility of this consistent J-dependence in (p,α) reactions in the 1p shell has been demonstrated. Since fairly recent results,[13] on L=2, J=3/2 and 5/2, (α,p) reactions in the (2s,1d) shell, fail to show similar consistency, comparable studies of (p,α) reactions in this heavier shell would be of interest.

FOOTNOTES AND REFERENCES

*Work performed under the auspices of the U. S. Atomic Energy Commission.

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7. No L=5 component in the transitions to the ^{12}C(14.08 MeV, 4+) and ^{10}B(6.03 MeV, 4+) final states is allowed under the assumptions of pure p-shell target nuclei and a pickup mechanism.

8. Unfortunately, a pure J=5/2 angular distribution can not be observed in the $^{12}C(p,\alpha)^{9}B$ transition to the 2.3 MeV states due to the presence of an unresolved J=1/2 component. This point will be discussed in our later publication.

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FIGURE CAPTIONS

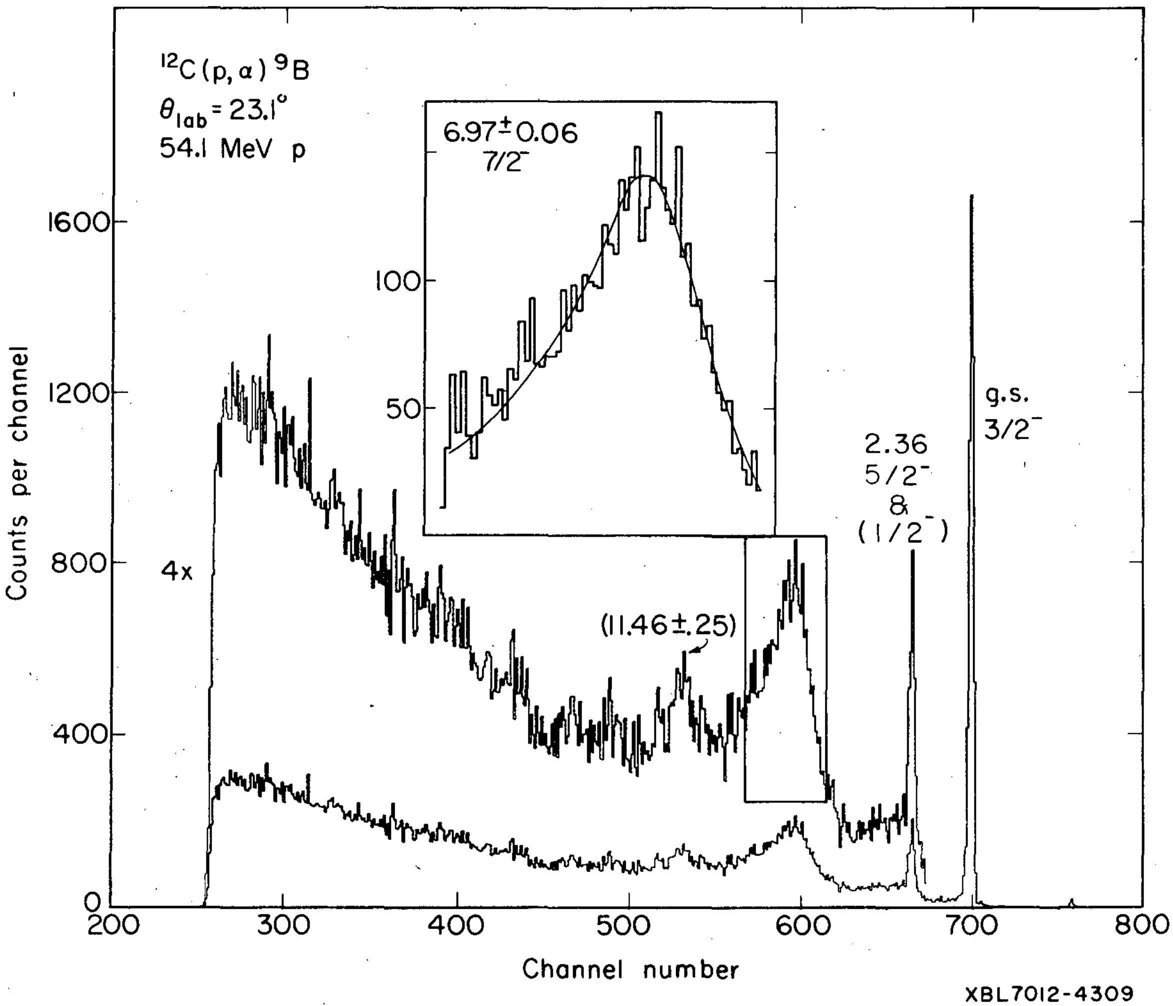
Fig. 1. The energy spectrum of the $^{12}C(p,\alpha)^{9}B$ reaction. The insert represents the indicated portion of the spectrum after removal of background; the curve shows an analytical fit to this consistently asymmetric peak.

Fig. 2. The energy spectrum of the $^{16}O(p,\alpha)^{13}N$ reaction. The insert shows a four-Gaussian fit to the indicated region of the spectrum, after background subtraction.

Fig. 3. Differential cross sections for various L=1 (p,α) transitions: (a) J=1/2 transitions; (b) J=3/2 transitions. Where error bars are not shown, they are smaller than the size of the points. The curves represent least-squares fits to the data. Vertical lines have been added to facilitate comparisons.

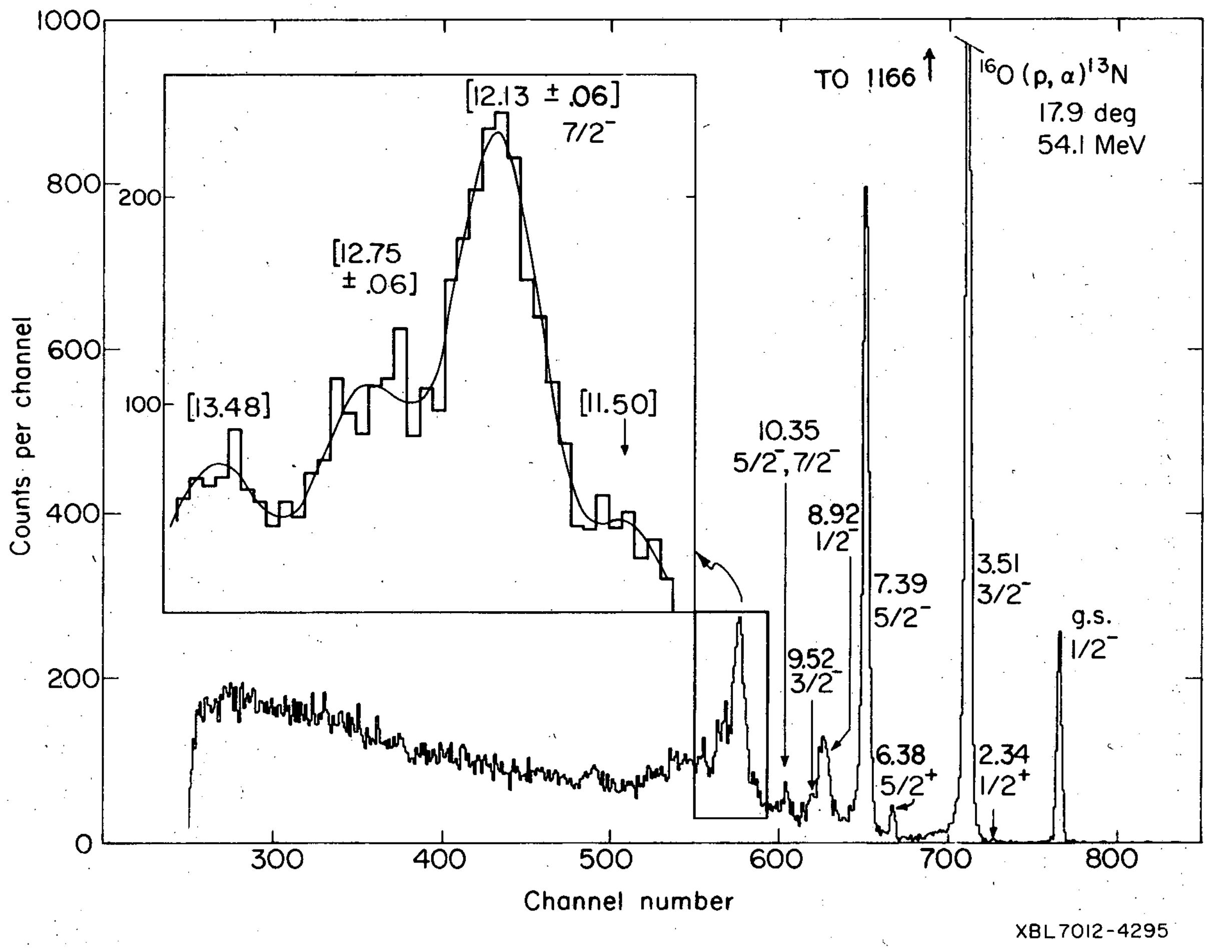
Fig. 4. Differential cross sections for various L=3 (p,α) transitions: (a) J=5/2 transitions; (b) J=7/2 transitions. See caption to Fig. 3.

Fig. 5. DWBA calculations for J=1/2, 3/2, 5/2, and 7/2 transitions in the $^{16}O(p,\alpha)^{13}N$ reaction. The solid curves are least-squares fits to the experimental data. Theoretical angular distributions are represented with broken lines; both J=1/2 and 3/2 calculations are shown for the ground-state transition for comparative purposes. The calculations are separately normalized to the data by a chi-squared minimization.



$^{12}C(p,\alpha)^9B$
$\theta_{lab}=23.1°$
54.1 MeV p
6.97±0.06
7/2⁻
100
50
1600
1200
800
400
0
4x
Counts per channel
(11.46±.25)
2.36
5/2⁻
&
(1/2⁻)
g.s.
3/2⁻
200
300
400
500
600
700
800
Channel number
XBL7012-4309

Fig. 1



1000
800
600
400
200
0
200
100
Counts per channel
300
400
500
600
700
800
Channel number
[12.13 ± .06]
7/2⁻
[12.75
± .06]
[13.48]
[11.50]
TO 1166
$^{16}O(p,\alpha)^{13}N$
17.9 deg
54.1 MeV
10.35
5/2⁻, 7/2⁻
8.92
1/2⁻
7.39
5/2⁻
3.51
3/2⁻
9.52
3/2⁻
g.s.
1/2⁻
6.38
5/2⁺
2.34
1/2⁺
XBL 7012-4295

Fig. 2

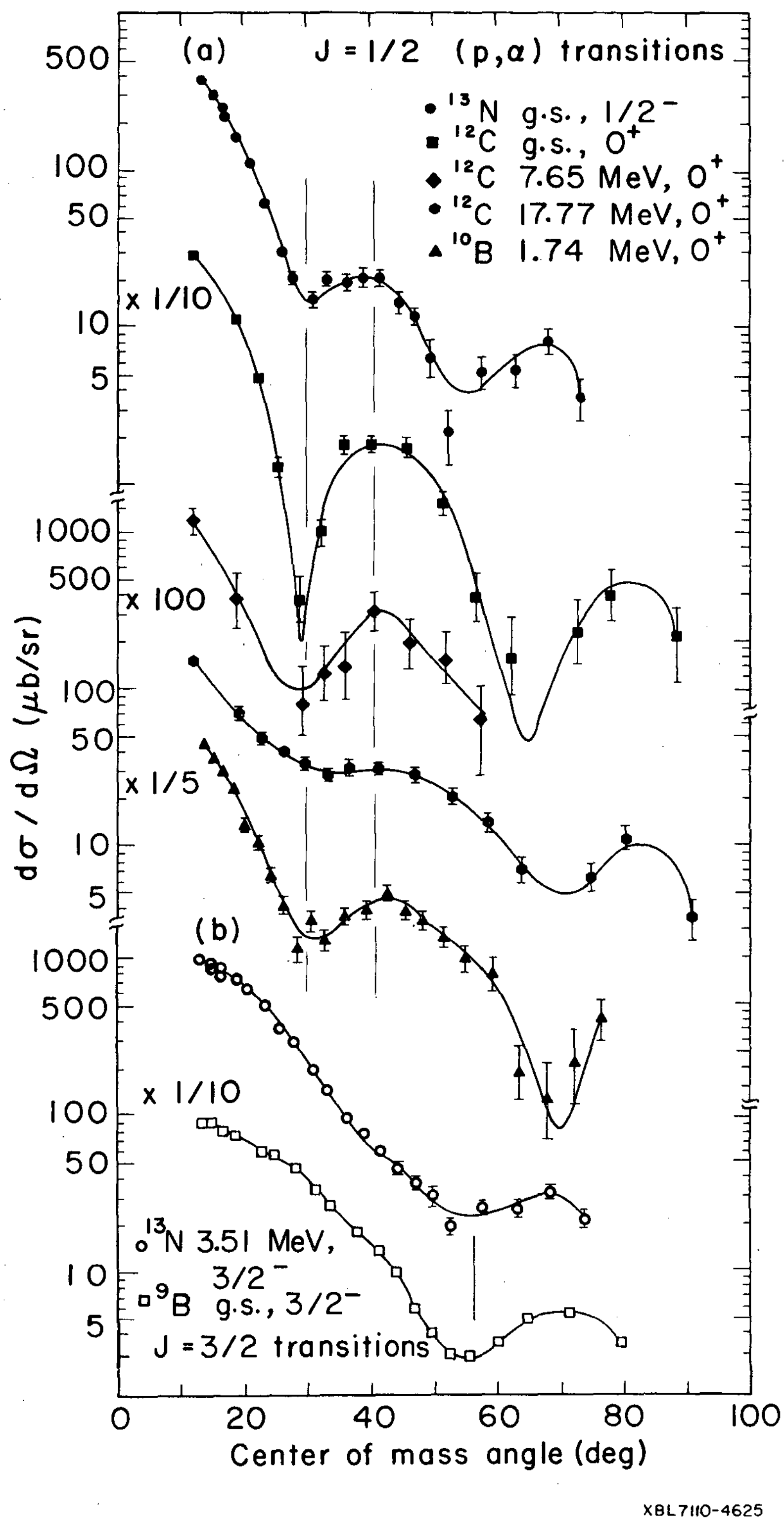

(a) J = 1/2 (p,α) transitions
• 13N g.s., 1/2−
■ 12C g.s., 0+
◆ 12C 7.65 MeV, 0+
● 12C 17.77 MeV, 0+
▲ 10B 1.74 MeV, 0+
x 1/10
x 100
x 1/5
(b)
x 1/10
o 13N 3.51 MeV, 3/2−
□ 9B g.s., 3/2−
J = 3/2 transitions
dσ / dΩ (μb/sr)
Center of mass angle (deg)
XBL7110-4625

Fig. 3

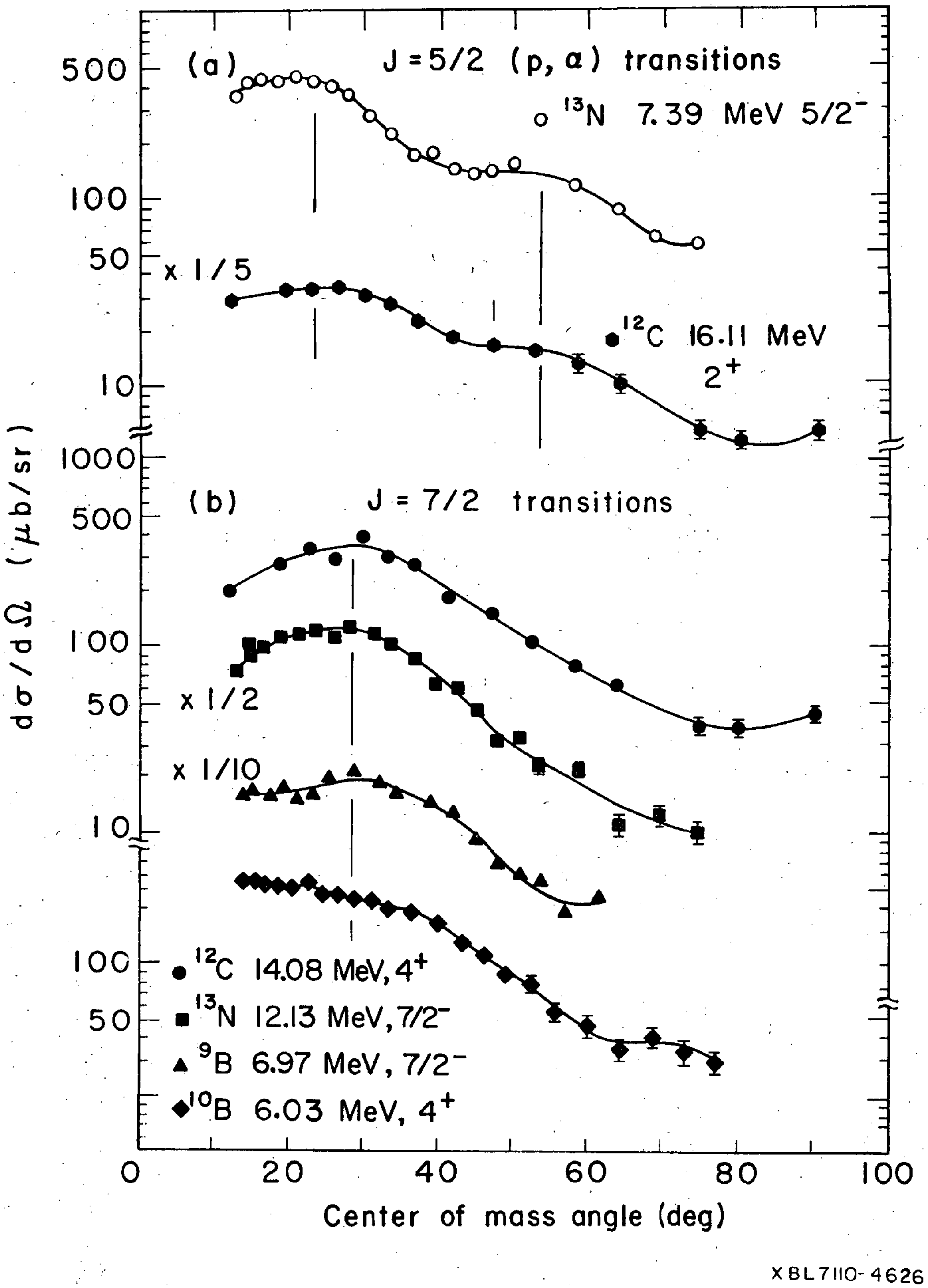
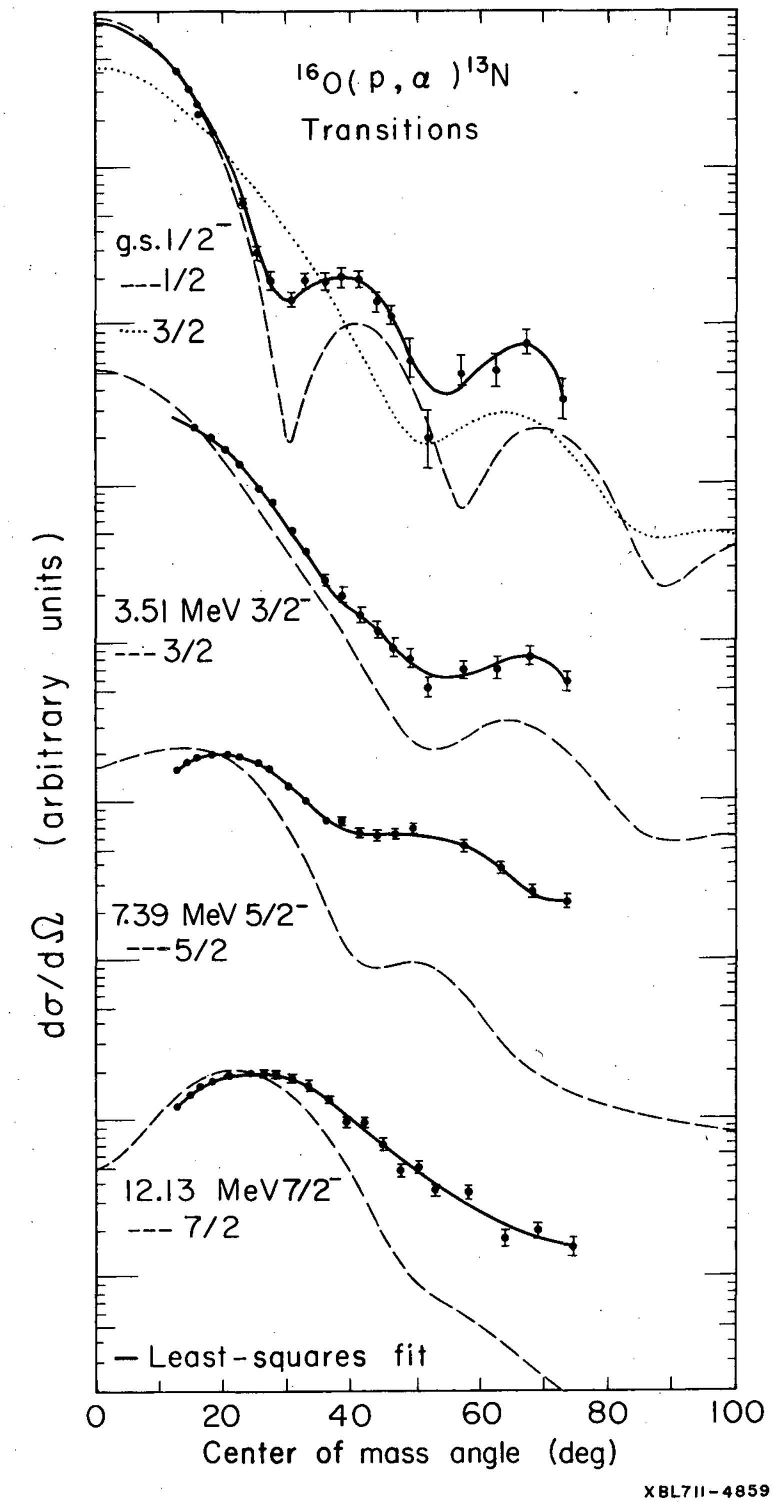

(a) J = 5/2 (p, α) transitions
○ ^{13}N 7.39 MeV 5/2$^-$
x 1/5
● ^{12}C 16.11 MeV 2$^+$
(b) J = 7/2 transitions
x 1/2
x 1/10
● ^{12}C 14.08 MeV, 4$^+$
■ ^{13}N 12.13 MeV, 7/2$^-$
▲ ^{9}B 6.97 MeV, 7/2$^-$
◆ ^{10}B 6.03 MeV, 4$^+$
dσ/dΩ (μb/sr)
Center of mass angle (deg)
XBL 7110-4626

Fig. 4



$^{16}O(p, \alpha)^{13}N$
Transitions
g.s. 1/2⁻
---1/2
·····3/2
3.51 MeV 3/2⁻
---3/2
7.39 MeV 5/2⁻
---5/2
12.13 MeV 7/2⁻
---7/2
— Least-squares fit
dσ/dΩ (arbitrary units)
0
20
40
60
80
100
Center of mass angle (deg)
XBL711-4859

Fig. 5

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