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Isospin violation in the $^{12}C(^6Li,\alpha)^{14}N(2.31\ MeV)$ reaction

J. P. Sokol† and C. P. Browne
Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556
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The isospin violating reaction $^{12}C(^6Li,\alpha)^{14}N$(2.31 MeV) was investigated in the range of beam energies from 9.0 to 14.0 MeV. Excitation functions were measured for the ground state, 2.31-MeV state and 3.95-MeV state of ^{14}N at 15°, 20°, 60°, and 160°. Excitation functions were taken at 40° for the ground state and 3.95-MeV states. Angular distributions were obtained at 10.5-, 11.25-, 12.5-, 13.75-, and 20.0-MeV beam energies. The cross section for the isospin forbidden reaction to the 2.31-MeV state is 0.4 to 1.8% of that to the allowed ground state and 3.95-MeV state in the beam energy range 9 to 14 MeV. At 20.0 MeV the yield to the forbidden state is only 0.02% of the allowed yield. Isospin mixing by the Coulomb force is believed responsible for the forbidden yield observed between 9–14 MeV.

[NUCLEAR REACTIONS $^{12}C(^6Li,\alpha_0,\alpha_1,\alpha_2)$, $E=9$–14, 20 MeV; measured $\sigma(\theta, E_{^6Li})$. Enriched target. Deduced isobaric spin violation.]

Investigations of the isospin forbidden reaction $^{12}C(^6Li,\alpha)^{14}N$(2.31 MeV) with beam energies of up to 6.0 MeV have shown isospin violations as high as 30%.[1-3] Other studies at beam energies as high as 33 MeV have shown no yield to the 2.31-MeV state, usually because the experiment was not designed to study isospin violation.[4-6] The purpose of this study was to observe this yield at beam energies above 9 MeV with a view to determining the reaction mechanism.

Lithium beams with energies of up to 20.0 MeV were produced by an FN tandem accelerator. Enriched carbon targets of 20 and 40 $\mu g/cm^2$ which had a ^{13}C content of $<0.02\%$ were used, and α particles leading to the first three states of ^{14}N were detected with an array of 100- and 300-μm totally depleted silicon detectors. The α particles were stopped in the detectors, but deuterons and protons lost very little energy and did not interfere with the α groups of interest. Between 40° and 140° detectors subtended a solid angle of 3.4×10^{-3} sr, whereas 0.87×10^{-3} sr, was subtended at forward and backward angles. A detector at 40° served as a monitor and allowed comparisons with data taken by other researchers.[3,4] At 15° a 50-cm, broad-range magnetic spectrograph with a position sensitive proportional counter in the focal plane was used in order to minimize the background from elastically scattered lithium ions. The energy resolution was 75–125 keV for the spectrograph run, 125–175 keV for solid state detectors at angles ≤40°, 150–225 keV at angles >140°, and 200–300 keV at central angles.

Cross-section scales for the yield curves were obtained by comparing the yield of the $^{12}C(d,\alpha)^{10}B$ reaction at 10.5 MeV with the results of Smith and Richards.[7] Experimental uncertainties are as follows: For the reproducibility of a yield curve or angular distribution, ±18%; for the value of the differential cross sections shown for the angular distributions and yield curves, ±30%; for the total cross section ±35%. For the low cross section of the 2.31-MeV state (α_1 group), 25% to 50% statistical uncertainty must be added to the 35% experimental uncertainty for a range of total uncertainty of 43% to 60%.

Figure 1 shows a spectrum taken with a solid-state detector at 60° and a beam energy of 11.5 MeV. Alternate channels were summed to obtain the points shown. The groups from $^{12}C(^6Li,\alpha)^{14}N$ leading to the ground state (g.s.) and the 3.95-MeV state of ^{14}N are shown at the far right and left, respectively. The group leading to the 2.31-MeV state is between the groups leading to the g.s. and 0.097-MeV states of ^{18}F, from $^{16}O(^6Li,\alpha)^{18}F$. The vertical bars on either side of the group leading to the 2.31-MeV state of ^{14}N show the channel limits between which the counts were summed. The nearly horizontal line represents the assumed background. The yield to the 2.31-MeV state is 1.1% of the average yield to the ground state and 3.95-MeV state in this case.

Yield curves for the first three states in ^{14}N were measured at angles of 15°, 20°, 40°, 60°, and 160°. The 2.31-MeV group was obscured at 40° by the ground-state group from the $^{16}O(^6Li,\alpha_0)^{18}F$ reaction. Below 12 MeV a heavy contaminant (probably barium) in the targets made it necessary to take data at 140° rather than 160° for the ground state. For the allowed states, preliminary data were taken at 40° in 100-keV steps from 10 to 12 MeV. As no rapid fluctuations were seen, 200-

and 250-keV steps were used for the remaining data. Unpublished $^{14}N(\alpha,\alpha_1)^{14}N$ data taken by Parker and Baglin in 60-keV steps from 18–25 MeV show no finer structure. As the beam energy is increased above 14 MeV, the α_1 group from $^{12}C(^6Li,\alpha_1)$ becomes obscured by groups from the $^{16}O(^6Li,\alpha)\,^{18}F$ reaction. Below 9 MeV the transmission through the accelerator was too low to extend the yield curve.

Figure 2 shows the yields to the ground state, first excited state, and second excited state of ^{14}N. The region in ^{18}F spanned by the ^6Li beam energy of 9 to 14 MeV is 19.22 to 22.55 MeV. The only structure in the ground-state yield curve at forward angles is in the region of 11.0-MeV beam energy ($E_x = 20.56$ MeV). At 160° a peaking is seen at 13.0 MeV ($E_x = 21.89$ MeV). The 160° yield curve for the first excited state shows maximum values at 11.5 MeV ($E_x = 20.88$ MeV) and to a lesser extent at 13.0 MeV ($E_x = 21.89$ MeV). In agreement with Ref. 4, the yield to the second excited state at 40° shows structure around 11.7 and 12.8 MeV. On the 40° plot, using triangles for the α_0 group and squares for the α_2 group, we show the data of Johnson and Waggoner.[4] By comparison with the angular distributions shown in Ref. 4, we conclude that the yield curves in Fig. 6 of Ref. 4 must be in the c.m. system. We converted these values to the laboratory system and multiplied by 1.5 to produce the points shown in Fig. 2. Our angular distribution datum for α_0 at 49.5° (c.m.) and 11.25 MeV bombarding energy is 0.59 mb/sr (c.m.) and that from Ref. 4 at this angle and 11.2 MeV is about 0.55 mb/sr. Our α_0 total cross section at 11.25 MeV is about 20% larger than theirs at 11.2 MeV. Thus the factor of 1.5 in the yield curves arises from a combination of our errors in normalizing angular distributions and yield curves and uncertainties in the absolute cross sections of both measurements. The discrepancy is consistent with the various uncertainties. Yield variations with energy are very similar for the two measurements. Finally, we note that Johnson and Waggoner divide the data of Dzubay[3] by 1.4 to obtain agreement with their yield curves taken at

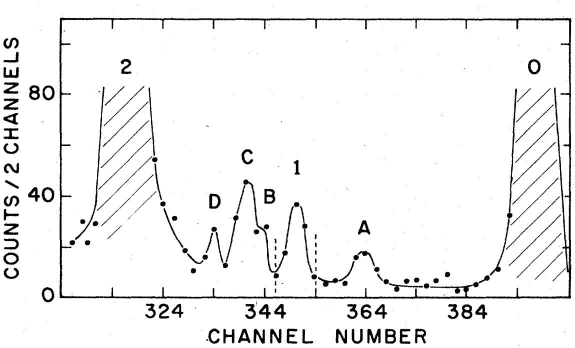

FIG. 1. Example of a $^{12}C(^6Li,\alpha)^{14}N$ spectrum taken with a solid-state detector. Alternate channels have been summed. Groups from the $^{16}O(^6Li,\alpha)^{18}F$ reaction leading to the g.s., 0.94-, 1.04-1.11 (mixed), and 1.70-MeV states are labeled with A, B, C, and D respectively. The groups leading to the g.s., 2.31-, and 3.95-MeV states of ^{14}N are labeled with 0, 1, and 2, respectively. Observation was at 60° with a 11.5-MeV beam energy.

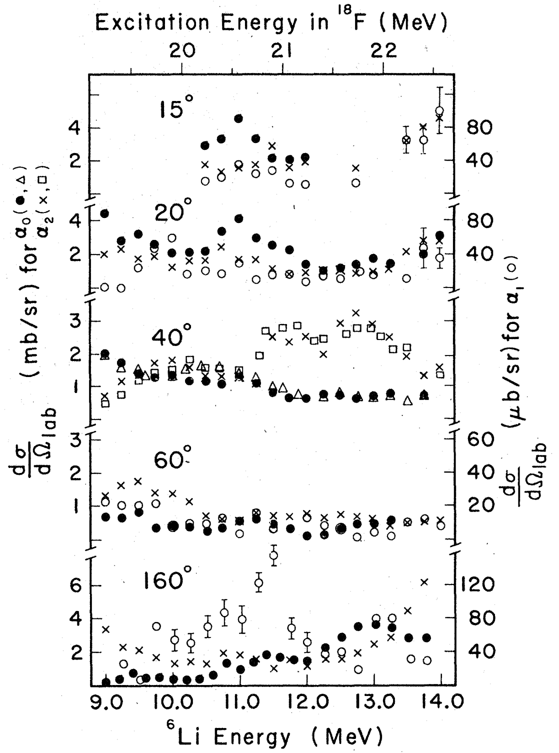

FIG. 2. Differential cross sections for $^{12}C(^6Li,\alpha)^{14}N$ as a function of lithium bombarding energy at laboratory angles of 15°, 20°, 40°, 60°, and 160° for the ground state, 2.31-MeV, and 3.95-MeV states of ^{14}N. The ground state is represented by solid circles, the 2.31-MeV state by open circles, and the 3.95-MeV state by crosses. The right-hand ordinate scale applies to the open circles, the left-hand scale to the other symbols. Where error bars are not shown, the statistical uncertainty is no larger than twice the size of the data point. Data for the ground state below 12 MeV were measured at 140° rather than 160°. The triangles (for the g.s.) and squares (for the 3.95-MeV state) on the 40° plot show the data of Johnson and Waggoner multiplied by 1.5. See text.

$\theta_{1ab} = 0°$ (again reading the ordinates of their Figs. 5 and 6 in the c.m. system).

Angular distributions for the three states taken at laboratory energies of 10.5, 11.25, 12.5, 13.75, and 20.0 MeV are shown in Fig. 3. The 10.5 and 12.5-MeV values were chosen as relatively unstructured regions on either side of the 11.25-MeV region. The 13.75-MeV energy was chosen for a distribution because it was near the high end of the yield curve. The 20.0-MeV distribution was taken to compare this work with that done previously by Meier-Ewert.[5] The data for the $T=1$ state at 20.0 MeV represent an estimate of the upper limit of the cross section. Except for a few cases no yield above background was discernible.

As a means of getting the total cross section from the angular distributions, they were fitted with Legendre polynomials. Polynomials of orders 0 to 14 were tried. The solid lines in the figure show the most reasonable fits. In the case of the 2.31-MeV state, where the presence of the oxygen contaminant limits the number of data points, a straight line often represents the best fit. Since the reaction to the first excited state involves a spin-parity system $0^+1^+ \to 0^+0^+$, the cross sections must go to zero at 0° and 180°. This is indicated by the dashed triangles in Fig. 3, and these values were entered in the fitting routine. The most reasonable Legendre polynomial fits to the rather limited data available for the weak forbidden group do not go through zero at the end points. Since the small and large angle portions of the curve contribute very little to the total cross section, these errors at the end points cause only a small part of the error assigned to the total cross section (the desired result of the measurement). Constraining the fits to go to zero at the end points produces polynomials of higher order than is physically reasonable and may give poorer fits at the more significant central angles.

Because of the oxygen contamination the yield curves were not continued above 14 MeV, so the normalization of the angular distributions taken at a beam energy of 20 MeV was based on the $(^6\mathrm{Li}, \alpha_{0,2})$ cross sections of Meier-Ewert,[5] instead of the (d,α) cross sections[7] used for the yield curves. We measured the ratios of the 2.31-MeV state yield to the yields of the ground state and the 3.95-MeV state and then used the Meier-Ewert cross sections to derive the 2.31-MeV cross section. The ratio of the ground state to the 3.95-MeV state cross sections from the two experiments differs by less than 10%.

These cross sections are used to derive the isospin violations for the forbidden reaction leading to the 2.31-MeV state. The violation (V) is

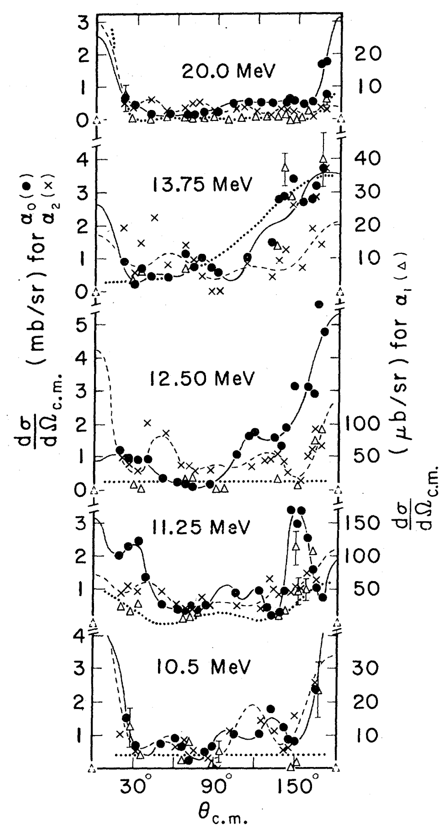

FIG. 3. Angular distributions of alpha particles from the reaction $^{12}\mathrm{C}(^6\mathrm{Li}, \alpha)^{14}\mathrm{N}$ for the ground state, 2.31-MeV state, and 3.95-MeV state of $^{14}\mathrm{N}$ at the beam energies shown. The ground state is represented by solid circles and a solid line, the 2.31-MeV state by triangles and a dotted line, and the 3.95-MeV state by crosses and a dashed line. The right-hand ordinate scale applies to the triangles, the left-hand scale to the other symbols. The curves are polynomial fits. Where error bars are not shown, the statistical uncertainty is no larger than twice the size of the data point.

$$V = \frac{k \times 2\sigma(\alpha_1)}{\sigma(\alpha_0) + \sigma(\alpha_2)},$$

where $\sigma(\alpha_0)$, $\sigma(\alpha_1)$, and $\sigma(\alpha_2)$ are the cross sections for the ground state and first two excited states of $^{14}\mathrm{N}$. The k is a statistical factor that depends on the spins of the particles. If k is approximated by $(2J_f + 1)$, where J_f is the J value of the final state, it has the value 3. Jolivette suggests[8] that $k=5$ would be more appropriate. In Table I, V is given in percentages for both k factors.

The total cross sections listed in Table I for $^{14}\mathrm{N}(\alpha, \alpha_1)^{14}\mathrm{N}$ come from the unpublished data of Parker and Baglin.

There are few measurements of the forbidden reaction in the $^{14}N+\alpha$ channel in our energy range. One is that of Jolivette[8] on $^{16}O(d,\alpha)^{14}N$. His result, shown in Table I, of 7% violation in the ^{18}F excitation energy range 19–20 MeV matches our values between 20.7 and 22.4 MeV. (Our value at 20.22 MeV seems low.) We also show in Table I the results of Johnson and Waggoner for α_0 and α_2 groups from our reaction (they did not measure α_1). These agree with our results. Finally we list α_0 and α_2 cross sections for the (d,α) reaction from Yanabu *et al.*[9], and α_1 cross sections for (α,α) from Parker and Baglin. The α_2 cross sections from the (d,α) and $(^6Li,\alpha)$ reactions are remarkably alike and those of the α_0 are within a factor of about 2. The α_1 cross sections from (α,α) are a factor of about 2 to 4 larger than those of the $(^6Li,\alpha)$ reaction.

The isospin violation seen in this experiment can be attributed to mixing in the compound system. The low yield for the 2.31-MeV state at a beam energy of 20.0 MeV (excitation of 26.55 MeV in ^{18}F) perhaps indicates that this energy is in the region where isospin conservation holds because of the dynamic criterion. No evidence was seen to indicate the presence of a direct-reaction contribution to the yield.

A comparison of $^{16}O(d,\alpha)^{14}N$, $^{14}N(\alpha,\alpha)^{14}N$, and $^{12}C(^6Li,\alpha)^{14}N$ indicates that the compound nucleus mechanism probably predominates at 19 to 23 MeV in the compound system and care should be exercised in applying direct reaction theory at even these high excitations in ^{18}F.

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TABLE I. Total cross sections and isobaric spin violations for three reactions forming the compound nucleus ^{18}F. Cross sections for the g.s., 2.31-MeV, and 3.95-MeV state of ^{14}N are listed under α_0, α_1, and α_2, respectively.

E_x in ^{18}F (MeV)	Cross section (mb) α_0	α_1	α_2	I-spin violation (V) (%) $k=3$	$k=5$
$^{12}C(^6Li,\alpha)$ (Present work and Johnson and Waggoner[a])					
19.89[a]	8.18		7.84		
20.22[b]	13±3	0.05 ±0.02	13±3	1.2	2.0
20.69[a]	10.80		8.54		
20.72[b]	13±3	0.16 ±0.05	10±2	4.2	7.0
21.22[a]	9.59		7.77		
21.56[b]	13±3	0.15 ±0.05	11±2	3.7	6.2
21.58[a]	10.71		7.09		
22.39[b]	14±2	0.18 ±0.09	10±2	4.5	7.5
22.55[a]	8.34		8.46		
26.55[b]	6±2	0.001±0.0005	4.5±2	0.06	0.1
$^{16}O+d$ (Jolivette[c] and Yanabu *et al.*[d])					
19–20[c]	9.2	0.14	10.9		7
20.77[d]	7.0		12.1		
21.48[d]	4.9		13.5		
22.19[d]	5.9		10.5		
24.95[d]	3.6		5.5		
$^{14}N+\alpha$ (Parker and Baglin[e])					
20.36		0.22			
20.66		0.28			
21.43		0.28			
22.54		0.57			

[a] See text Ref. 4.
[b] These lines give the present results.
[c] Results from text Ref. 8.
[d] Results from text Ref. 9.
[e] P. D. Parker and C. M. Baglin (unpublished); see text.

†Present address: at Westinghouse Advanced Nuclear Systems Division, Madison, Pennsylvania.

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