Isospin-Forbidden $^{16}O(d, \alpha_1)^{14}N$ Reaction*

J. JOBST,† S. MESSELT,‡ AND H. T. RICHARDS
University of Wisconsin, Madison, Wisconsin 53706
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Differential cross sections for the isospin-forbidden reaction $^{16}O(d, \alpha_1)^{14}N^*$ are reported for $3<E_d<15$ MeV for various angles. For $5<E_d<9$ MeV, data points are 10–20 keV apart and at six angles. Many resonances are observed. Detailed angular distributions have been taken at some of the resonances and the data interpreted in terms of ^{18}F states with large isospin mixing. For some of these states, J^π assignments are obtained. No evidence appears for any appreciable direct-reaction yield.

INTRODUCTION

THE implication of isospin conservation for nuclear reactions was discussed in some detail by Adair,[1] and the low yield of the $^{16}O(d, \alpha_1)^{14}N$ reaction to the $T=1$ level at $E_x(^{14}N)=2.31$ MeV was specifically cited as an example. Browne[2] studied this reaction at selected energies and angles for $5.5<E_d<7.5$ MeV and concluded that the yield of the forbidden group was about 7% of the allowed ground state group. This same order of magnitude for relative intensity has been confirmed by several other workers[3–8] at a few isolated energies. Browne also observed some evidence for resonant character to the yield. Hashimoto and Alford[9] pointed out that, even in the absence of isospin conservation, the unnatural parity of the deuteron inhibits (d, α) reactions between zero spin target and zero spin residual states by a factor of three. This inhibition results because only compound nuclear states with $J=l$ and parity $=(-)^l$ can decay by α emission to a zero spin residual nuclear state whereas compound states of $J=l$, and $l\pm1$ and parity $(-)^l$ can be formed. A further relative inhibition of isospin forbidden alphas to the 2.31-MeV state of ^{14}N arises from the unfavorable statistical weight of this 0^+ state compared with the adjacent 1^+ ground and 3.95-MeV states of ^{14}N. This discrimination gives another factor of three relative inhibition so, even in the absence of isospin conservation, one expects an order of magnitude reduction in α yield to the $J=0^+$ $E_x=2.31$ state of ^{14}N. It would therefore appear that the scant data on the reaction would suggest large isospin nonconservation.

The object of the present experiment was to obtain data extensive enough in energy and angle to confirm the resonant character of the yield, to study the compound nuclear states of ^{18}F involved, and to explore the excitation range of apparent isospin nonconservation.

EXPERIMENTAL ARRANGEMENTS

For most of the work the experimental arrangements and energy ranges covered were the same as those reported by Jobst[10] on the simultaneously measured isospin-allowed reactions. Some additional problems arose in our effort to extend the cross-section data for the isospin forbidden group to lower energies ($E_d<5$ MeV). Since the Q for the isospin forbidden group is small ($Q=+0.799$ MeV), it becomes increasingly difficult at low E_d to separate this weak low-energy group from the intense deuteron and proton groups always present. To discriminate optimally against these groups requires that the depletion layer of the solid state detector be just thick enough to stop the desired α_1 group; but then the intense, more energetic α_0 group is not stopped and may contribute a broad interfering group of pulses. Separation at the forward angle was usually easier than the back angles. At certain angles and deuteron energies clean separation was not achieved. These problems limited our results to $E_d>3$ MeV.

Since the α_1 cross section is typically $\lesssim 100$ μb/sr, statistical uncertainties usually dominate. Systematic uncertainties (see Ref. 10) probably are $\sim 3\%$. Only statistical uncertainties are shown on the figures. Target thicknesses are always ≤ 13 keV: The incident beam is homogeneous in energy to <2 keV.

ENERGY SCALE

A word of caution is needed concerning the deuteron energies quoted in this paper. After the data had been analyzed and the figures prepared, evidence accumulated that there were unsuspected but large nonlinearities in our analyzer magnet calibration. A

* Work supported in part by the U.S. Atomic Energy Commission.
† Present address: EG & G, Inc., 680 East Sunset Road, Las Vegas, Nev. 89101.
‡ Present address: Institute of Physics, University of Oslo, Oslo, Norway.
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TABLE I. Some ^{18}F states with large isospin impurities.

$E_x(^{18}F)$[a] (MeV)	J^π	E_d[a,b] $^{16}O(d,\alpha_1)^{14}N$ (MeV)	E_α[a] $^{14}N(\alpha,\alpha_1)^{14}N$[c] (MeV)
10.43	3^-	3.29	
10.51	$2^+ + (1^-, 3^-)$	3.37	
10.63	2^+	3.51	
10.75	2^+	3.65	
10.95	2^+	3.86	
11.00	2^+	3.93	
11.07	2^+	4.01	
11.13	3^-	4.07	
11.29	$3^- + (4^+5^-)$	4.25	
11.96	$(1^-) + (3^-)$	5.00	
12.10		(5.2)	9.88
12.43	$3^- + (2^+)$	5.53	···
12.43 }d	$4^+ + (2^+3^-)$	···	10.32
12.51 }d	$4^+ + (2^+3^-)$	5.62	···
12.62 }d	5^-	···	10.55
12.68 }d	5^-	5.81	
13.06	(4^+)	6.24	
13.31 }d	5^-	···	11.43
13.33 }d	5^-	6.55	···
13.57	$(5^-, 3^-)$	6.81	···
13.67 }d	$4^+ + (2^+)$	···	11.90
13.68 }d	$(4^+) + (3^-)$	6.94	···
13.79	(4^+)	···	12.05
13.80	3^-	7.08	···
13.98		···	12.30
14.12 }d	$5^- + (4^+)$	7.43	···
14.16 }d	$5^- + (3^-)$	···	12.52
14.31	4^+	···	12.72
14.47	(4^+)	7.84	···
15.56	3^-	9.03	···
16.45	4^+	10.04	···

[a] These excitation energies correspond roughly to cross-section maxima. Interference effects may shift such peaks $\approx\Gamma$ from the resonant ^{18}F state.
[b] The energy scale has been corrected for magnet recalibration (see text) and will not correspond exactly to Figs. 1–7.
[c] Reference 17.
[d] Probably a single state (the energy shifts may result from interference) but there is some contrary indication (see text).

thorough recalibration by J. C. Davis indicates that our absolute energy is low by $\sim$0.6% for $E_d > 9$ MeV. As E_d decreases, the error decreases to 0.4% at 5 MeV and 0.1% at 3 MeV.

We have not redrawn our figures but the energies in Table I have been corrected to remove this systematic uncertainty. A table of these energy corrections was appended to Ref. 10, p. 1161.

RESULTS

The $3 < E_d < 5$ MeV excitation data in 20 keV steps at $\theta = 30°$ c.m. (center-of-mass) and $\theta = 143°$ c.m. are shown in Fig. 1.[11] The reason for choosing these angles will become apparent in the next section especially from a consideration of Fig. 8, where it is clear that the yield at $\theta \simeq 30°$ will be very sensitive to $l = 2$, 3, and 4; moderately sensitive to $l = 1$ and 5; and insensitive only to $l = 6$. The yield at $\theta = 143°$ (equivalent to 37°) c.m. will still be relatively sensitive to $l = 2$, 3, and 4 and hence show strong interference effects between odd and even l by the asymmetry in yield about 90° c.m. From Fig. 1 the resonant character of the reaction is evident, but the strong lack of symmetry about $\theta = 90°$ also shows that interference effects are important. Angular distributions were taken at energies indicated by arrows on Fig. 1 and are displayed in the first two columns of Fig. 2.

The most intensively studied energy range was $5 < E_d < 9$ MeV, and the excitation functions in 10–20

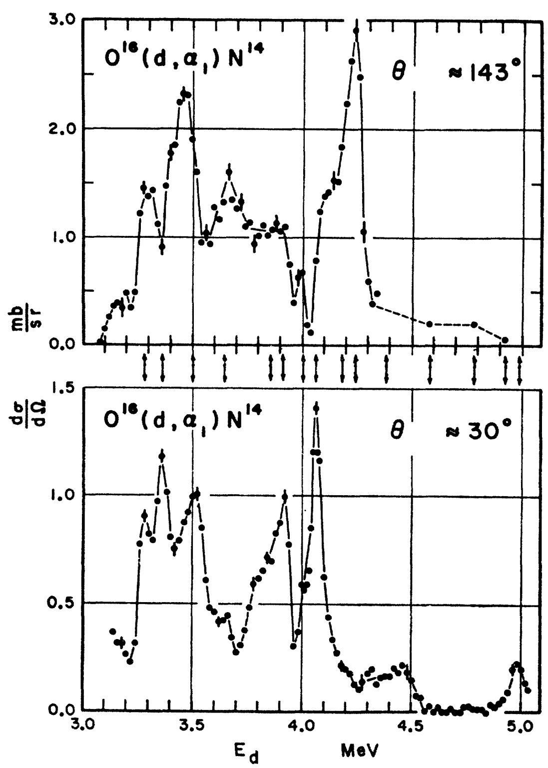

FIG. 1. Low-energy excitation function for the isospin-forbidden $(d\alpha)$ reaction to the first $T = 1$ state of ^{14}N at $E_x(^{14}N) = 2.31$ MeV. Arrows indicate E_d at which detailed angular distributions were also taken. Representative statistical errors are shown.

[11] Preliminary low-energy data ($E_d < 5$ MeV) were reported by one of the authors (Messelt) at the Isobaric Spin Conference, Tallahassee, Fla., March 1966. See S. Messelt, in *Isobaric Spin in Nuclear Physics*, edited by J. D. Fox and D. Robson (Academic Press Inc., New York, 1966), p. 814.

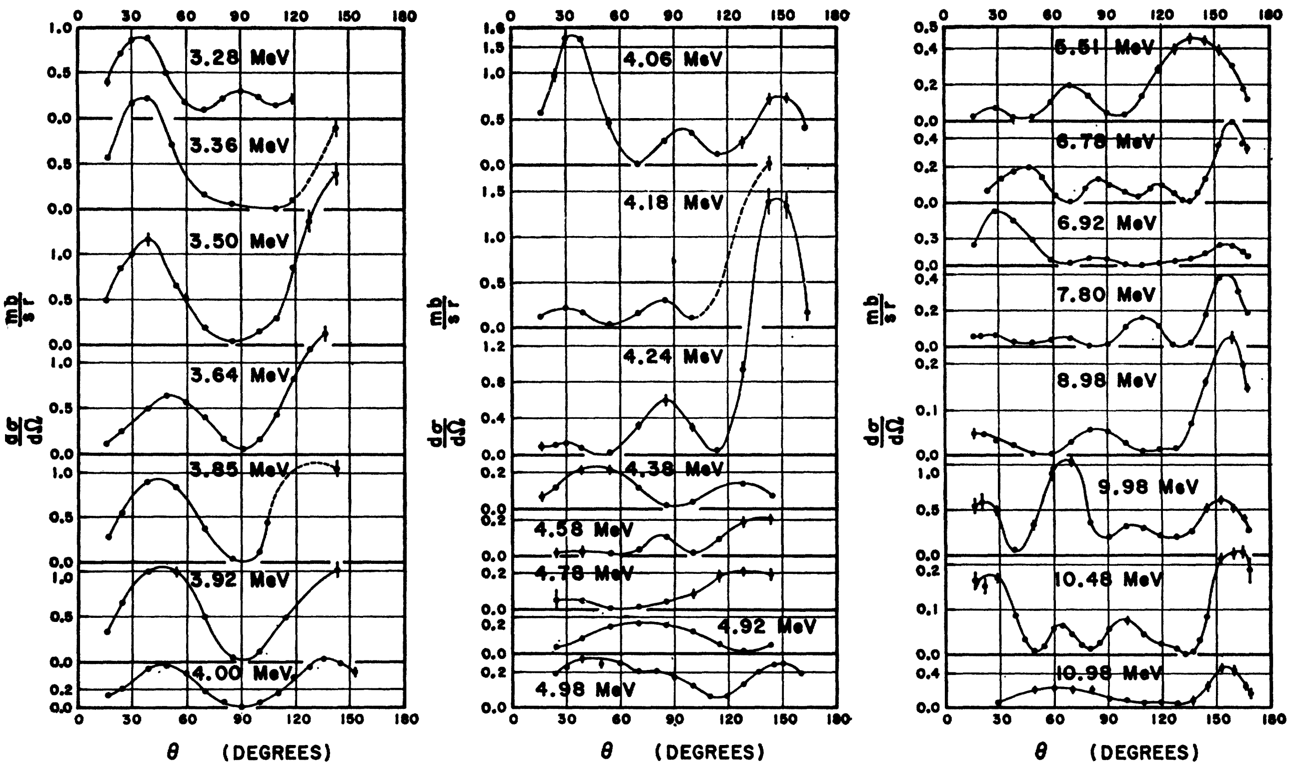

FIG. 2. Center-of-mass differential cross sections for the isospin-forbidden α. Each curve is labeled with the deuteron energy (E_d) which was usually chosen to correspond to a maximum in the ($d\alpha_1$) excitation curves, Figs. 1, 3, and 6.

keV steps for six angles are shown in Fig. 3. Angular distributions, taken at selected energies, are shown in Figs. 2 and 4.

The neighborhood of the intense peak at forward and backward angles near $E_d=5.78$ MeV (Figs. 3 and 4) was the subject of more careful study. Five angular distributions were taken, at $E_d=5.74$–5.82 MeV, in 20-keV steps (see Fig. 5), in the hope of better displaying the interference effects and helping fix the resonant energy.

Figure 6 shows some back angle survey data $9<E_d<15$ MeV taken with the counter telescope (Ref. 10). Coarse energy steps were taken over most of the energy region but the region 12.4 MeV$<E_d<$13.6 MeV was looked at in small energy increments to ascertain whether there were any narrow resonances at these higher excitation energies. It would seem that resonant structure is still apparent. Some forward angle survey data were also obtained (Fig. 7).

DISCUSSION OF RESULTS

The same factors which inhibit α_1 in the absence of isospin selection rules (see introduction) also simplify greatly the interpretation of the results: the zero spin of all reaction members except the deuteron and the unnatural parity of the deuteron require that the outgoing l be the same as the incoming l; the states of the compound nucleus ^{18}F are hence fixed uniquely by the l value and can only be $J=1^-$, 2^+, 3^-, 4^+, etc. (The value $l=0$ is excluded because only a $J=1^+$ compound state could be formed and such a state cannot decay into two $J^\pi=0^+$ particles.)

Because of the above restrictions, the α-particle angular distributions are particularly simple and can be easily calculated. One can always express the differential reaction cross section in the form[12,13]

$$d\sigma_{\alpha's';\alpha s}=\frac{\bar{\lambda}_\alpha^2}{2s+1}\sum_{L=0}^{\infty}B_L(\alpha's',\alpha s)P_L(\cos\theta)d\Omega.$$

The coefficients B_L, for a single isolated resonance, can be obtained from tables of Z coefficients.[13–15] The angular distributions so calculated for $l=1$–6 are shown in Fig. 8. Since these distributions are symmetric about 90°, only the 0°–90° portion is shown.

Some qualitative features of these angular distributions merit comment: All cross sections vanish at $\theta=0°$ and 180°; the number of maxima in the range $\theta=0°$–180° is just equal to the l value of the resonance (and hence fixes J^π of the compound nuclear state); all even l have

[12] J. M. Blatt and L. C. Biedenharn, Rev. Mod. Phys. **24**, 258 (1952).

[13] A. M. Lane and R. G. Thomas, Rev. Mod. Phys. **30**, 257 (1958).

[14] W. T. Sharp, J. M. Kennedy, B. J. Sears, and M. G. Hoyle, Atomic Energy of Canada Limited Report No. AECL 97 (unpublished).

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a zero at $\theta=90°$ and all odd l have a maximum at 90°; the number of cross-section zeros in the range $\theta=0°$–180° is equal to $l+1$.

Hence even a qualitative inspection of angular distribution data can yield considerable information. For example, Fig. 2 shows clearly that at $E_d=3.92$ MeV the angular distribution is very nearly that expected from a single isolated $J=2^+$ state of ^{18}F while at $E_d=$ 4.06 MeV the most important contribution is from a $J=3^-$ state of ^{18}F. For the $E_d=4.06$-MeV data the lack of complete symmetry about 90° and the failure of the cross section to go completely to zero at $\theta=117°$ demonstrate interference with a neighboring *even* J state of ^{18}F (probably the $J=2^+$ state at $E_d=4.00$ MeV).

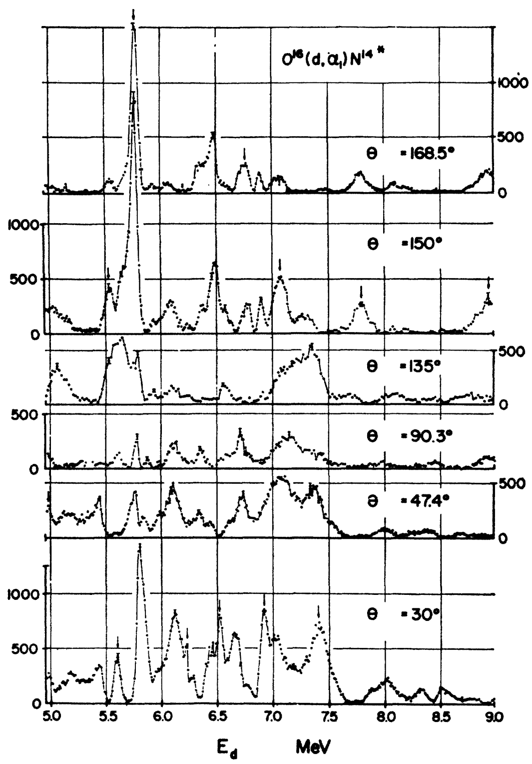

FIG. 3. Similar to Fig. 1 except for higher E_d and more angles.

The $E_d=7.04$-MeV data (Fig. 4) again show a predominantly $l=3$ pattern. The intense resonance at $E_d=5.78$ has five maxima (see also Fig. 5) and hence requires a $J=5^-$ state in ^{18}F. In both cases some interference with another state or states is evident.

When interference effects are really large, the interpretation becomes much more difficult; e.g., at $E_d=5.60$ MeV (Fig. 4) the forward angle data ($\theta<90°$) suggest strong $l=4$, but the back angle data ($\theta<90°$) show such interference that the corresponding minimum expected at $\theta=130°$ has become a maximum. Jolivette[16] has

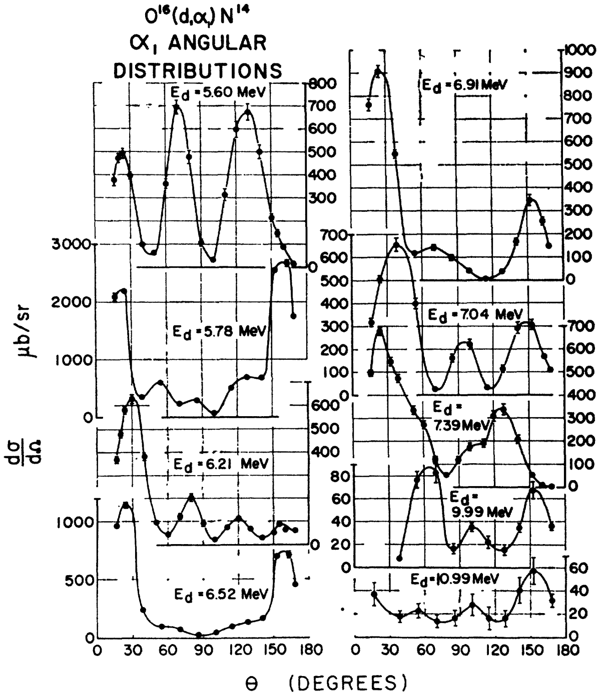

FIG. 4. Similar to Fig. 2. Statistical uncertainties are shown only when they are larger than the point size.

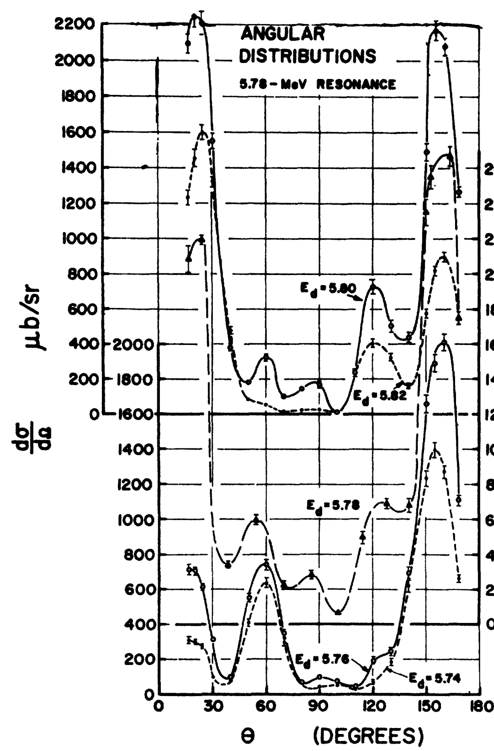

FIG. 5. Detailed study of the angular distributions (center-of-mass) of the isospin forbidden α's in the neighborhood of the intense resonance at $E_d \cong 5.78$ MeV.

[16] P. Jolivette, Bull. Am. Phys. Soc. 12, 1172 (1967); and (private communication).

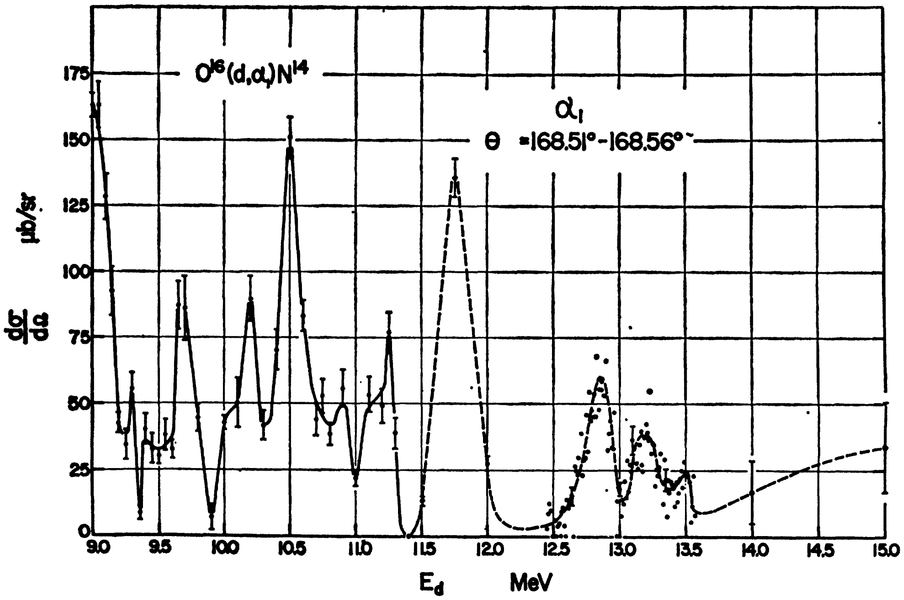

FIG. 6. Similar to Fig. 1 except for higher E_d and at extreme back angle.

obtained good quantitative fits of most of these angular distributions. To adequately fit the $E_d=5.60$ MeV data requires large amplitudes of at least three l values. However, $l=4$ is always one of the major amplitudes.

Table I lists states in ^{18}F which may be implied by resonances in the isospin forbidden cross section. However, it should be emphasized that Table I does not include all states in ^{18}F which our data suggest, but only those which were studied in some detail. The angular distribution data were so time consuming that only a sampling of the resonances could be undertaken. Angular distributions were usually taken only at maxima in the cross section where hopefully a single state of ^{18}F might dominate. However, the asymmetries about 90° clearly warn of interference effects. The column J^π gives the assignment based upon a qualitative inspection of the angular distribution (Figs. 2 and 4). Quantitative analyses by Jolivette[16] confirm most of these assignments. When interference effects are obviously very important, there is sometimes also listed the J^π of the suspected interfering level or levels. Parentheses enclose the more doubtful assignments.

A word of caution is needed concerning the energy of the ^{18}F states: Because of the omnipresent interference effects of neighboring levels, the peaks in the cross section at which the angular distributions were taken will not in general correspond exactly to the resonant energy. One may expect shifts of the order of the width of the resonances, which here seems to be $\sim$100 keV. This estimate seems confirmed by some other

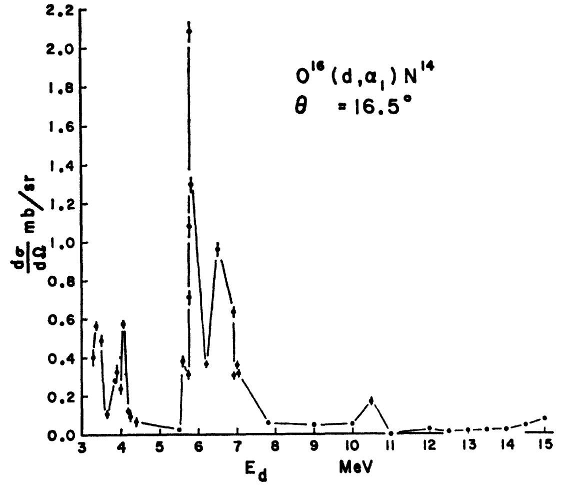

FIG. 7. Excitation function at extreme forward angles constructed from Fig. 2, 4, and 5, plus some early counter-telescope survey data.

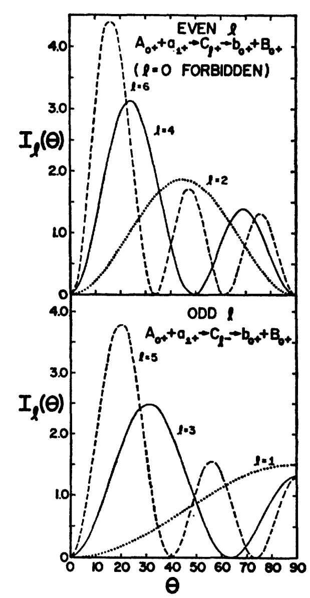

FIG. 8. Unique theoretical angular distributions for outgoing zero-spin even-parity particles from an isolated state J of a compound nucleus formed by a 0^+ and 1^+ pair of incident particles. For such a case $l=l'$, $J^\pi=l^{(-)^l}$, and $l\neq 0$.

TABLE II. Comparison of cross sections for isospin-allowed α groups (α_0 and α_2) with the isospin-forbidden α group (α_1). The average is for 5 MeV$<E_d<$9 MeV.

Group	$\langle\theta_i\rangle$ (deg)	$\langle\sigma_{\alpha_i}(\theta)\rangle$ (mb/sr)	$\langle\sigma_{\alpha_i}\rangle$ (mb)
α_0	29.4	8.66	42.0
	46.5	5.20	
	88.9	3.98	
	133.9	3.75	
	149.2	6.54	
	168.1	9.73	
α_1	30.0	0.278	1.13
	47.4	0.165	
	90.3	0.077	
	135.0	0.136	
	150.0	0.176	
	168.5	0.093	
α_2	30.7	5.14	33.3
	48.4	4.69	
	91.9	2.92	
	136.3	2.80	
	150.9	4.93[a]	
	168.9	12.53	

[a] This value was not equally weighted in calculating $\langle\sigma_{\alpha_2}\rangle$ because data for $E_d<6.25$ MeV were incomplete.

data in Table I (Ref. 17) on ^{18}F levels excited by the isospin-forbidden ^{14}N$(\alpha,\alpha_1)^{14}$N reaction. Where their data overlap ours, a few resonances in the α_1 yield are seen. Angular distributions at these resonances can be analyzed in exactly the same manner as ours. While their data are much less extensive (their angular range, 50°–110° c.m., is particularly limited), they quote J^π assignments for most of their cases. Their assignments are based upon Legendre polynomial fits of their differential cross sections.

TABLE III. Change in average total cross sections as $f(E_d)$ for α_0, α_1, and α_2.

	$\langle\sigma_{\alpha_i}\rangle$		
Group	$E_d\geq5$ MeV ≤7.5 MeV (mb)	$E_d\geq7.5$ MeV ≤9 MeV (mb)	Decrease (%)
α_0	48.3	32.0	34
α_1	1.58	0.45	71
α_2	35.4[a]	29.4	17

[a] The term $\langle\sigma_{\alpha_2}(\theta_n)\rangle$ for $\theta_n\simeq150°$ is weighted by a factor of $\frac{1}{2}$ since the α_2 cross section is incomplete for $E_d<6.25$ MeV.

It will be noted that in most cases where they have a firm assignment, we also find a similar assignment from the $(d\alpha_1)$ reaction but displaced in $E_x(^{18}\text{F})$ by $\lesssim80$ keV: e.g., the $4^+(2^+,3^-)$ assignments at $E_x=12.43$ and 12.51 MeV, the 5^- assignments at $E_x=12.62$ and 12.68 MeV, and again 5^- at 13.31 and 13.33 MeV $E_x(^{18}\text{F})$. These neighboring ^{18}F states, seen by different channels but with same J^π (which in Table I we have joined by brackets) probably correspond to only one ^{18}F state. Interference effects could produce the observed shifts in peak energy. However, there is some evidence which should caution us about making this identification. In particular, one notes at lower E_x a number of examples of closely spaced levels of the same J^π which are seen via a single channel. The observed cross sections for these reactions require large violations of isospin conservation. These violations arise, we believe, from states of ^{18}F of the same J^π but different

TABLE IV. Ratio (as a function of E_d) for isospin forbidden (α_1) and allowed (α_0 or α_2) differential cross sections at $\theta\simeq168.5°$.

Group	$\langle\sigma_{\alpha_i}(\theta)\rangle$ 5 MeV$\leq$ $E_d\leq$9 MeV (mb/sr)	Ratio $\sigma_{\alpha_1}/\sigma_{\alpha_0,\alpha_2}$	$\langle\sigma_{\alpha_i}(\theta)\rangle$ 12.4$<E_d<$ 13.6 MeV (mb/sr)	Ratio $\sigma_{\alpha_1}/\sigma_{\alpha_0,\alpha_2}$
α_0	9.73	0.96%	1.82	1.4%
α_1	0.093		0.025	
α_2	12.53	0.74%	0.97	2.6%

isospin which lie close enough that Coulomb forces will appreciably mix the isospin. If the product $\Gamma_d\Gamma_{\alpha_1}$ are comparable for two levels, both may be observed (or both missed). If either Γ_d or Γ_{α_1} is small for one state compared to the other, then only one ^{18}F state may show in the $d\alpha_1$ channel. For the $(\alpha\alpha')$ data[17] the relevant product of partial widths is of course $\Gamma_{\alpha_0}\Gamma_{\alpha_1}$ so we should not be surprised if there were numerous cases where one of the admixed ^{18}F states had a large $\Gamma_{\alpha_0}\Gamma_{\alpha_1}$ when the other had a small $\Gamma_d\Gamma_{\alpha_1}$ or vice versa. If such be the case, then the different channels may be selecting different members of the J^π doublets.

The doublet nature of these ^{18}F states may indeed be a common feature of isospin violation in self-conjugate nuclei. The 2^+ doublet in ^{8}Be is an example[18] for self-conjugate even nuclei. The odd self-conjugate nuclei for a given E_x have a much higher level density than the neighboring even self-conjugate nuclei. Therefore it would not be surprising if in ^{18}F there were many examples of such nearly degenerate states whose configurations can be expanded in mirror clusters and hence neither state can be an eigenstate of the total isobaric spin.

[17] C. M. Chesterfield and B. M. Spicer, in *Isobaric Spin in Nuclear Physics*, edited by J. D. Fox and D. Robson (Academic Press Inc., New York, 1966), p. 734; and (private communication).

[18] J. B. Marion, P. H. Nettles, C. L. Cocke, and G. J. Stephenson, Jr., Phys. Rev. **157**, 847 (1967).

ORIGIN AND MAGNITUDE OF THE ISOPIN VIOLATIONS

A violation of the isospin selection rule may be caused by impurity in the initial, final, or compound nuclear states. MacDonald[19] estimates the impurity in ^4He, ^{14}N, and ^{16}O ground states to be 0.001, 0.2, and 0.4%, respectively, and these values should also apply to low-lying excited states. The deuteron isospin impurity may likewise be neglected. Furthermore, the observed isospin violation is of a resonant character, so we are encouraged to view the violation exclusively in terms of isospin impurities in ^{18}F intermediate states. From fluctuation analysis[10] of the concomitantly taken allowed $(d\alpha_i)$ reactions we obtain a $\langle\Gamma_{J^\pi}\rangle$ of $\sim$150 keV. From an extrapolation of known levels densities in ^{18}F we estimate the spacing between levels of the same J^π as $D_{J^\pi}\simeq 75$ keV. MacDonald[19] calculates the average matrix element of the isospin mixing Coulomb forces to be $\langle H_c\rangle\approx 100$ keV for these light nuclei. Hence we are in the region $\langle D_{J^\pi}\rangle\simeq\langle H_c\rangle\simeq\langle\Gamma\rangle$ which Wilkinson[20] long ago suggested to be most favored for isospin mixing. At still higher ^{18}F excitation energies one expects the increasing $\langle\Gamma\rangle$ to result finally in lifetimes short compared to Coulomb mixing times, $\hbar/\langle H_c\rangle$; hence isospin would again be conserved. The present data apparently do not overlap this region although there is some evidence that the magnitude of the violation is less for the upper part of our energy range. (See below and Figs. 3, 6, and 7, and Table III.)

Table II compares average differential and total cross sections for the isospin forbidden α_1 data (Fig. 3) with the adjacent allowed α_0 and α_2 data.[10] The averages are for 5 MeV$<E_d<$9 MeV. If the lower 2.5 MeV and upper 1.5 MeV of the energy range are separately averaged, Table III results and indicates that indeed the relative isospin violation is decreasing as the excitation energy increases. However, at still higher energy, 12.4 MeV$<E_d<$13.6 MeV, the trend reverses at least for $\theta_{\rm cm}=168.5°$ where large l partial waves are important. Table IV shows $\langle\sigma_{\alpha_1}\rangle/\langle\sigma_{\alpha_{0,2}}\rangle$ for both 5 MeV$<E_d<$9 MeV and 12.4 MeV$<E_d<$13.6 MeV. The apparent increase of isospin violation as E_d increases may be related to a bias for states of high J at $\theta=168°$ (see Fig. 8). The region of maximum isospin impurity is certainly a function of J (e.g., see p. 347 of Ref. 13). In fact one may expect that ^{18}F states of low J are sufficiently dense and broad at $E_x(^{18}F)=14$ MeV that isospin conservation for them could be reappearing while at the same time the higher spin states may just be entering an excitation region of maximum isospin violation since their level densities and widths could be relatively much smaller.

We next estimate the magnitude of the average isospin impurities in the ^{18}F states necessary to account for our data. As pointed out in our introduction one expects that, independent of isospin conservation, the $(d\alpha_1)$ reaction is inhibited by a factor of $\sim$9 compared to the allowed $(d\alpha_0)$ and $(d\alpha_2)$ reactions to the adjacent $J=1^+$ states of ^{14}N.

Since the Q value for the forbidden $(d\alpha_1)$ reaction is intermediate between the allowed $(d\alpha_0)$ and $(d\alpha_2)$ reactions, penetrability and phase space factors will be unimportant if we form the ratio

$$R_{\rm expt}=2\langle\sigma_{\alpha_1}\rangle/(\langle\sigma_{\alpha_0}\rangle+\langle\sigma_{\alpha_2}\rangle),$$

whereas from the discussion above we expect $R_{\rm theoret}\approx\frac{1}{9}[2f^2/(1-2f^2)]$, where f is the amplitude of the isospin impurity in the ^{18}F state. If one uses the average cross sections from Table II, we find[21]

$$\langle f^2\rangle\approx 11\%.$$

If one remembers that this is an average over a 4-MeV interval of ^{18}F states, then it would appear that at some individual resonances in the $(d\alpha_1)$ yield there may be negligible isospin caused inhibition.

The semidirect isospin mixing in deuteron reactions recently proposed by Noble[22] results from a short range nucleon-target spin orbit interaction which gives a preferential spin flip of one of the deuteron's nucleons because of the asymmetry introduced by the long-range Coulomb forces. Such a mechanism predicts an energy insensitive cross section which should be peaked at small angles. Not only are these qualitative features absent from our data but the order of magnitude of the effect would appear to be inadequate to account for our ratio of isospin forbidden to isospin allowed $(d\alpha)$ cross section.

More recently Noble[23] has extended his preferential spin-flip mechanism to the production of isospin impurities in purely compound reactions. It is not clear to what extent his recent considerations apply to the present data which we believe have high energy resolution ($\Delta E_d\sim$10 keV) compared to the width ($\sim$60–100 keV) and spacing of the involved individual ^{18}F states.

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