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Spin-parity combinations in ^{18}F

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We measured the tensor analyzing power T_{20} for the reaction ^{20}Ne($\vec{d}$,α)^{18}F for $E_x(^{18}\mathrm{F}) \leq 6.48$ MeV at $\theta_{\mathrm{lab}} = 176.3°$ and for incident deuteron energies of $10.5 \leq E_d \leq 12.0$ MeV in steps of 0.25 MeV. Comparison of the measured T_{20} values with theoretical predictions leads to assignments of natural or unnatural parity to about 30 levels in ^{18}F. Combining the present results with published spectroscopic information leads to new unambiguous J^π and isospin assignments for some levels and the confirmation of previously determined values for others.

[NUCLEAR REACTIONS ^{20}Ne($\vec{d}$,α), $10.5 \leq E_d \leq 12.0$ MeV; $\Delta E_d = 0.25$ MeV; measured $T_{20}(E, E_\alpha, 176.3°)$. ^{18}F deduced levels, natural target.]

I. INTRODUCTION

The ($\vec{d}$, α) reaction on even-even target nuclei initiated with tensor polarized ($m = 0$) deuterons and with the α particles detected near 0° or 180° can determine[1-3] whether the parity of levels in the odd-odd residual nucleus is natural or unnatural. If the incoming particle is in the $m = 0$ substate, the angular momentum of the final state of the residual nucleus is in the plane perpendicular to the beam axis. The 0° and 180° yields then depend[1,2] on the vector coupling coefficients $(L_1 0 S 0 | J'0), (L_2 0 J 0 | J'0)$ where L_1 is the orbital angular momentum brought in by the deuteron, S is the spin of the deuteron, J' is the total angular momentum of the intermediate state, L_2 is the orbital angular momentum carried off by the α particle, and J is the angular momentum of the final state. However, each of these vector coupling coefficients will vanish unless the sum of their angular momenta in each case is even. Since the deuteron has spin and parity 1^+, both coupling coefficients will be nonzero only for unnatural parity states of spin J, thus requiring $\pi = (-)^{J+1}$ for the parity of the residual nucleus. For a spin system $0^+ + 1^+ \rightarrow 0^+ + J^\pi$ where the outgoing particle is observed at $\theta = 0°$ or 180°, Boerma *et al.*[2] show that the tensor analyzing power T_{20} is independent of the energy and equals $1/\sqrt{2}$ for natural parity states while, within the framework of the statistical theory, T_{20} for unnatural parity levels (except 0^-) is uniformly distributed between the limits $1/\sqrt{2}$ and $-\sqrt{2}$. For $J^\pi = 0^-$, T_{20} is always[2,4] $-\sqrt{2}$. Furthermore, a $J^\pi = 0^+$ state will have zero yield at $\theta = 0°$ or 180° even for an unpolarized beam. Reference 5 gives the differential cross section for a reaction initiated with polarized particles of spin one in terms of the beam polarization t_{20} and the analyzing power T_{20} of the reaction. States of known natural parity have $T_{20} = 1/\sqrt{2}$ and so permit independent measurement of the beam polarization t_{20}.

For ^{18}F, the most recent Ajzenberg-Selove summary[6] reports definite J^π assignments for 32 of the 38 states with $E_x \leq 6.48$ MeV, whereas the 1972 summary[7] had only 24 definite assignments. Most of the new assignments come from the extensive studies by Rolfs *et al.*[8-10] The parity of four states at 4.226 ($J = 2$), 4.361 ($J = 1$), 4.860 ($J = 1$), and 5.502 MeV ($J = 3$) remained uncertain. A tentative assignment[10-12] (0^+, $T = 1$) exists for the state at 4.753 MeV and the 6.108 MeV state has a J of 1, 2, or $3^{(-)}$. Our present study uses tensor polarized deuterons with ^{20}Ne($\vec{d}$,α) ^{18}F to test the new assignments and to provide additional information on the structure of ^{18}F.

II. EXPERIMENTAL PROCEDURE

A momentum analyzed beam of tensor polarized ($m = 0$) deuterons from the University of Wisconsin Lamb shift polarized ion source[13] and EN tandem accelerator passed through differentially pumped apertures into a target chamber containing neutral neon. The collimating apertures of 1.02 mm outer

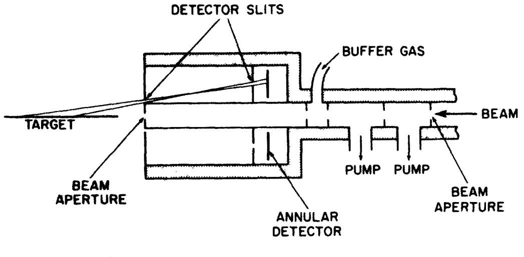

FIG. 1. Schematic diagram of the detector and slit system. (Not to scale.)

diameter were 464 mm apart. Helium gas introduced near the final collimator served as a buffer gas to reduce the neon flow to an acceptable rate. The gas pressure of 2.53 Torr corresponds to a target thickness of 0.6 keV at 11.5 MeV incident deuteron energy. Figure 1 shows a schematic diagram of the annular, fully depleted 72.7 μm thick surface barrier detector at $\theta_{\rm lab} = 176.3 \pm 1.2^\circ$ and the slit arrangment. The target length defined by the slit system was 34.5 mm. The distance from target center to detector was 75 mm. From Petty *et al.*'s[3] calculated attenuation of T_{20} for natural parity states, we concluded that the attenuation of T_{20} arising from θ being slightly less than 180° is less than 2% and so was ignored (see Sec. III).

III. DATA EXTRACTION AND RESULTS

Figure 2 shows typical α spectra for both unpolarized and tensor polarized ($m=0$) incident deuterons on the neon gas targets. We took spectra for $10.5 \leq E_d \leq 12.0$ MeV in steps of 0.25 MeV. The energy resolution of α particles was about 40 keV. The expanded spectrum (Fig. 3) from $E_x = 4$ to 7 MeV indicates that the positions of the α peaks agree with excitation energies[6] within ±3 keV. A peak fitting program subtracted background and extracted peak areas. α particles from the other neon isotopes ^{21}Ne(0.27%) and ^{22}Ne (9.2%) were not observed. The $^{22}\mathrm{Ne}(\vec{d},\alpha)\,^{20}\mathrm{F}$ cross sections[15] at $E_d \sim 10$ MeV are typically ~ 0.1 mb/sr whereas the $^{20}\mathrm{Ne}(\vec{d},\alpha)\,^{18}\mathrm{F}$ cross sections[16] are typically ~0.5 mb/sr.

We used the known natural parity states at excitation energies of 2.5234, 3.0612, and 3.13387 MeV to determine the beam tensor polarization, which was an average of $t_{20} \sim -0.3$ over several runs.

The values of T_{20} were obtained in the following manner: The ratio of the polarized to unpolarized yields (normalized to the same charge integration) was determined. This ratio is equal to one plus the product of the beam polarization t_{20} and the analyzing power T_{20}.[5] Knowing t_{20} allows us to calculate T_{20}.

The errors shown in Fig. 4 include counting statistics and also the uncertainties in t_{20}. Table I summarizes the results.

IV. DISCUSSION

The recent thorough investigation of the level structure of ^{18}F up to an excitation energy of

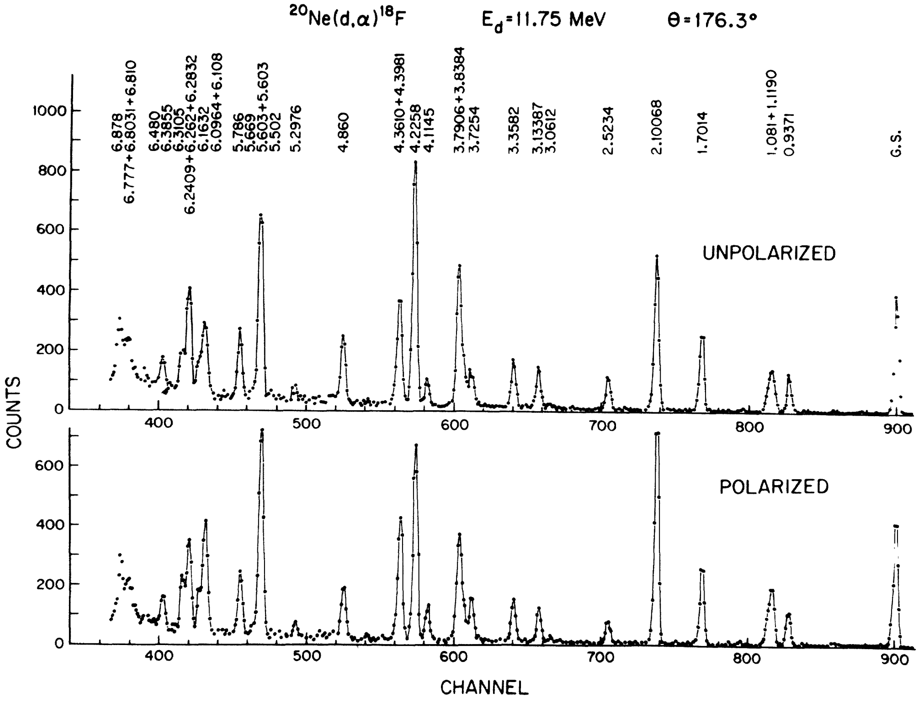

FIG. 2. Typical spectra for α particles from the reaction $^{20}\mathrm{Ne}(d,\alpha)^{18}\mathrm{F}$ for unpolarized and tensor polarized ($m=0$) incident deuterons. The labels above the peaks indicate the excitation energies of levels in ^{18}F in MeV taken from Ref. 6. The region below channel 360 was obscured by intense broad peaks resulting from deuterons not stopped in the thin detector.

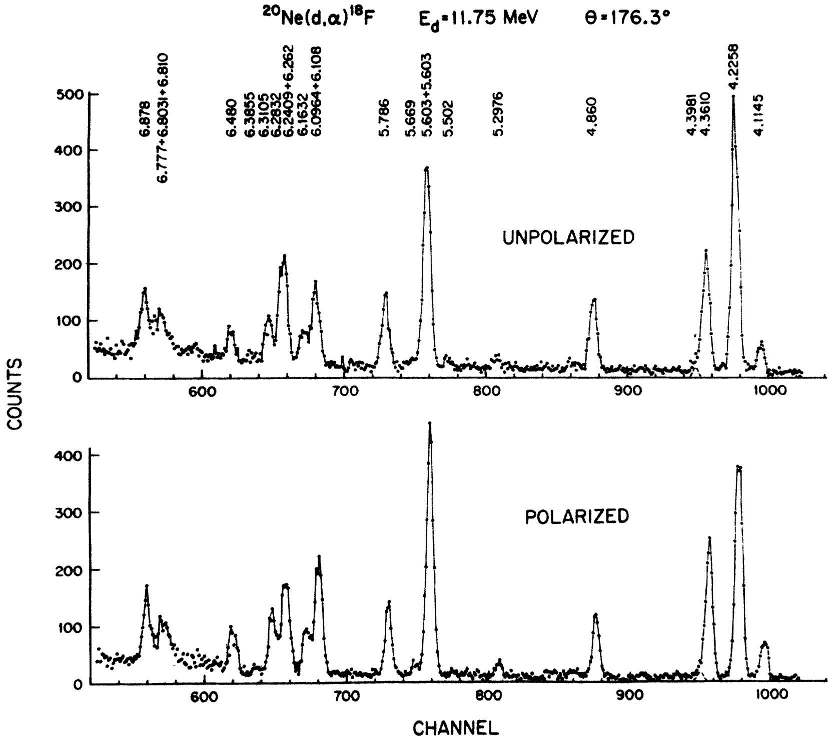

FIG. 3. High resolution α spectra obtained with a gated biased amplifier. Some overlapping peaks were successfully separated, as illustrated by the dashed line in the region of channel 950, by using a peak fitting routine.

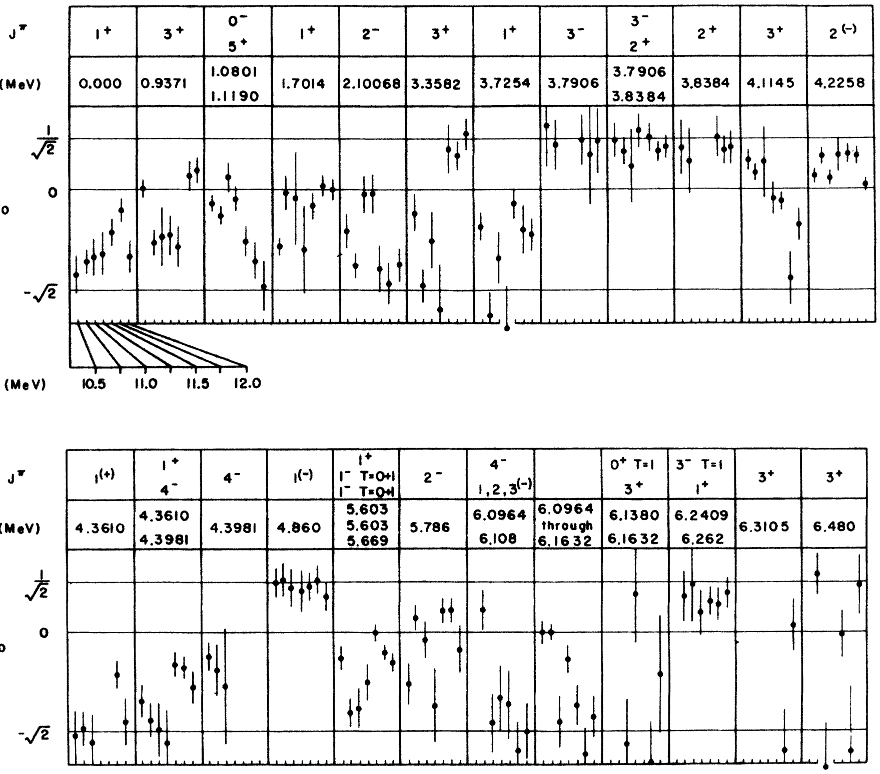

FIG. 4. Measured $T_{20}(176.3°)$ values for the ^{20}Ne(d,α) reaction to final states in ^{18}F. The top line indicates J^π and T assignments. Where T assignments are not given that level has $T=0$. The second line lists the excitation energies of the final state in MeV.

TABLE I. Spectroscopic information on levels in ^{18}F. N and U designate natural and unnatural.

E_x [a] (MeV)	J^π; T [a]	π	New assignments
0	1^+; 0	U	
0.9371	3^+; 0	U	
1.0410	0^+; 1		
1.0801	0^-; 0	U	
1.1190	5^+; 0		
1.7014	1^+; 0	U	
2.10068	2^-; 0	U	
2.5234 [b]	2^+; 0		
3.0612 [b]	2^+; 1		
3.13387 [b]	1^-; 0		
3.3582	3^+; 0	U	
3.7254	1^+; 0	U	
3.7906	3^-; 0	N	
3.8384	2^+; 0	N	
4.1145	3^+; 0	U	
4.2258	$2^{(-)}$; 0	U	2^-; 0
4.3610	$1^{(+)}$	U	1^+; 0
4.3981	4^-; 0	U	
4.652	4^+; 1		
4.753	(0^+; 1)		0^+; 1
4.860	$1^{(-)}$	N	1^-; 0
4.9636	2^+; 1		
5.2976	4^+; 0		
5.502	$3^{(-)}$; 0		
5.603	1^+	U	1^+; 0
5.603	1^-; 0 + 1		
5.669	1^-; 0 + 1		
5.786	2^-; 0	U	
6.0964	4^-; 0	U	
6.108	1, 2, $3^{(-)}$; 0		
6.1380	0^+; 1	U	
6.1632	3^+; 1		3^+; 0
6.2409	3^-; 1	(U + N) [c]	
6.262	1^+; 0		
6.2832	2^+; 1		
6.3105	3^+; 0	U	
6.3855	2^+; 0 + 1		
6.480	3^+; (0)	U	3^+; 0

[a] Spectroscopic information from Ref. 6.

[b] These natural parity levels were used to determine the beam polarization.

[c] Strong natural parity component though still some indication of unnatural parity. See (6) in Sec. IV; see also Fig. 4.

6.878 MeV by Rolfs *et al.*[8-10] confirmed all previous assignments but one. They disagree with the tentative assignment[17] of (4^+) to the 5.603 MeV state and instead make a firm 1^+ assignment. We could not resolve this state from the two nearby $J^\pi = 1^-$, $T(0+1)$ levels. Nevertheless our T_{20} extracted for the triplet shows (Fig. 4), by its large negative value, the dominance of the unnatural parity state and hence lets us assign $T = 0$. The absence of a corresponding 1^+ state in ^{18}O is consistent with our $T = 0$ assignment.

The additional assignments by Rolfs *et al.*[8-10] we now briefly discuss in connection with our results:

(1) Rolfs *et al.*[10] confirmed an earlier (3^-) assignment[18,19] for the 3.791 MeV state. We agree on the natural parity assignment.

(2) Their unambiguous 4^- assignment[10] for the 4.398 MeV state agrees with our unnatural parity requirement.

(3) The tentative (0^+, $T = 1$) assignment[10-12] for the 4.753 MeV level forbids any α yield at 180°. Our nonobservation of the α group near 180° supports either $J^\pi = 0^+$ or $T = 1$, or both. From our survey of the literature and our results, we believe a firm $J^\pi = 0^+$, $T = 1$ assignment is now indicated.

(4) Although we cannot resolve the 6.096 MeV (4^-) and 6.108 MeV [$J = (1, 2, 3^{(-)})$] states, our T_{20} (Fig. 4) extracted for the doublet shows the presence of at least one unnatural parity state. This result agrees with the reported[7] J^π assignments.

(5) The 0^+ assignment for the 6.138 MeV state rigorously forbids α emission at $\theta = 180°$ even for unpolarized deuterons and hence this state will not contribute appreciably at our angle ($\theta = 176°$) to the partially resolved group (Fig. 3 or 4) which we identify with the known 3^+ state at $E_x = 6.163$ MeV. When we separate out this group by peak fitting the T_{20} value agrees with the unnatural parity assignment, but the appreciable yield in our (d, α) reaction raises questions concerning the alleged $T = 1$ character. The $T = 1$ assignment comes from the lack of appreciable cross section in the ^{14}N + α channel [Sens *et al.*,[20] Silverstein *et al.*,[21] Herring *et al.*[22]]. However, one expects the analog state in ^{18}F [corresponding to the E_x (^{18}O) = 5.38 state] to be around 5.38 ± 1.04 ≃ 6.4 MeV in ^{18}F. Hence the known 3^+ states in ^{18}F at 6.31 and 6.48 MeV are more attractive $T = 1$ candidates. The current assignments of $T = 0$ to these states comes from the finite yield observed[8] in the ^{14}N + α channels and from the large yield Middleton *et al.*[19] observed in the ^{14}N(^{7}Li, t)^{18}F reaction. Since the latter reaction allows $T = 1$ final states the argument is not strong. Perhaps the simplest explanation corresponds to the 3^+ analog $T = 1$ strength being distributed over all three of these nearby 3^+ levels, but still allowing also appreciable $T = 0$ amplitudes.

(6) We do not resolve the 6.241 MeV (3^-, $T = 1$), 6.262 MeV (1^+, $T = 0$), and 6.285 MeV (2^+, $T = 1$) states. However, for the unresolved group the T_{20} near 180° stays near $1/\sqrt{2}$ and hence suggests that one or both of the $T = 1$ natural parity states dominate and, therefore, have appreciable $T = 0$ admixture. Rolfs *et al.*[10] have suggested such a possibility for the 6.241 MeV state.

(7) The 6.480 MeV (3^+) state has unnatural parity (Fig. 4) and the excitation strength observed in the ^{20}Ne($\vec{d},\alpha$)^{18}F reaction suggests predominantly $T=0$ character (though not excluding some $T=1$).

The discussion of our new assignments for ^{18}F levels follows.

A. 4.226 MeV state

The mean lifetime of 110 ± 15 fs for the 4.226 MeV state reported by Rolfs *et al.*[10] is too short to allow higher multipolarity than $E2$ or $M2$ in the decay. Their observation of the transition to the ground state (1^+) therefore limits $J \leq 3$. They argue that the strength for the transition from the 6.241 MeV ($3^-, T=1$) state to the 4.226 MeV state indicates $J=2$ or 3. Their analysis of the angular distribution of the same transition then leads uniquely to $J=2$. The strength of the transition from the 4.226 MeV state to the 1.080 (0^-) state suggests an $E2$ transition and hence negative parity. We observe unnatural parity for this state and therefore unambiguously assign $J^\pi=2^-$ to the 4.226 MeV state.

B. 4.361 MeV state

Rolfs *et al.*[9] assign $J=1$ to the 4.361 MeV state because for $J=2$ the observed 2% transition from the 0^+, $T=1$ state at 6.138 MeV would imply at least 770 W.u. (Weisskopf units) for an $E2$ and 17 700 W.u. for a $M2$ transition. The lifetime of the 4.361 MeV state of 27 ± 10 fs and the 100% branch to the 2^+, $T=1$ state at 3.061 MeV are consistent with $J=1$. They suggest positive parity since the assumption $J^\pi=1^-$ leads to $E1$ transition strengths for the above transitions of ~0.013 and 0.03 W.u., whereas the eight other $\Delta T=1$ transitions consistently result in $E1$ strengths of less than 0.003 W.u. Since our data require unnatural parity for the 4.361 MeV state we definitely assign $J^\pi=1^+$. Our excitation strength as well as the $M1$ transition strengths to and from nearby $T=1$ levels and the absence of a corresponding 1^+ state in ^{18}O all indicate a $T=0$ assignment.

C. 4.860 MeV state

Rolfs *et al.*[10] report a mean lifetime of 66 ± 18 fs for the 4.860 MeV state and a decay scheme that includes transitions to the 1.041 MeV (0^+, $T=1$) and 1.080 MeV (0^-) levels. Their results imply multipolarities no higher than $M2$ or $E2$ and hence $J=1$ or 2. Their analysis of the angular distribution of the γ transition from the 6.643 MeV (2^-, $T=1$) state to the 4.860 MeV level observed in the reaction ^{14}N(α,γ)^{18}F leads to a unique $J=1$. Gorodetzky *et al.*[11] also obtained $J=1$ in an ^{16}O(^{3}He, $p\gamma$)^{18}F correlation study. The tentative negative parity assignment[10] is based on the systematics of the γ decay of ^{18}F and the empirical observation[14] that ^{15}N(^{6}Li, t)^{18}F favors the negative parity states. We observe that the state is of natural parity and therefore assign unambiguously $J^\pi=1^-$ to the 4.860 MeV state.

Again, our α strength of this state together with Rolfs *et al.* data on the $M1$ transition strength to this level from a higher $T=1$ state would require a $T=0$ assignment.

V. CONCLUSIONS

The present experiment provides spectroscopic information on most of the first 38 states in ^{18}F. Our work confirms many recent assignments and gives several new assignments. Most of the states not seen were either 0^+ or $T=1$ and hence involved forbidden (or strongly inhibited) reactions.

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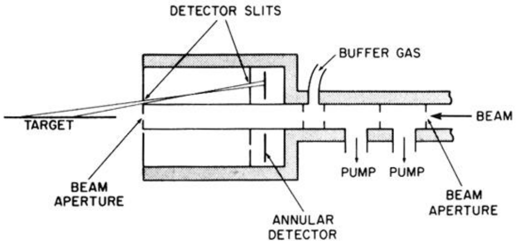

FIG. 1. Schematic diagram of the detector and slit system. (Not to scale.)