PHYSICAL REVIEW C VOLUME 18, NUMBER 5 NOVEMBER 1978

Search for simple configurations in ^{18}F. II. The $^{17}O(p,\alpha_0)^{14}N$, $^{17}O(p,p_1\gamma)^{17}O$, and $^{17}O(p,\gamma)^{18}F$ reactions

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(Received 28 November 1977)

Nineteen resonances corresponding to excitations between 6.9 and 8.3 MeV have been observed in $^{17}O+p$ reactions between $E_p = 1400$ and 2800 keV. From the Breit-Wigner analysis of the excitation function shapes for the various outgoing channels, resonance strengths were obtained and the partial widths deduced. Branching ratios of the γ rays were determined and in one case the γ-ray angular distribution could be measured and used for J^π assignment. A reaction Q value of 5604 ± 2.5 keV was found.

[NUCLEAR REACTIONS $^{17}O(p,\alpha_0)$, $^{17}O(p,p_1\gamma)$, and $^{17}O(p,\gamma)$, $E_p = 1.4-2.8$ MeV; measured $\sigma(E_p,\theta)$, Q. ^{18}F deduced levels, J^π, Γ, T. Enriched target.]

INTRODUCTION

Most of the experimental data on ^{18}F levels for $7 \leq E_x \leq 10$ MeV have been obtained from one or two nucleon transfer reactions which may give useful information about the main components of the wave function. However, in order to use completely such information, characterization of the quantum properties of the levels is required, and up to now very few such assignments have been made unambiguously.[1]

Basic shell-model considerations show that several states with simple configurations involving the $d_{3/2}$ and $2p$ shells are expected to be located between 7 and 10 MeV excitation. States with configurations such as $(d_{5/2}d_{3/2})$ or $(d_{5/2}2p)$ can readily be excited through $^{17}O+p$ reactions. Moreover, the ^{18}O level spectrum presents five levels between 6.19 and 7.11 MeV, whose analog states in ^{18}F should lie between 7 and 8.4 MeV.

A study of the various outgoing channels of the $^{17}O+p$ reaction has been undertaken in the incident energy range $E_p = 1.4-2.8$ MeV to investigate levels by resonant reactions. These offer both precise excitation energy determinations and a good energy resolution which are necessary to clarify the confusing situation in ^{18}F in this energy range. A previous article,[2] referred to as I, dealt with the analysis of the $^{17}O+p$ elastic scattering anomalies. The present paper will deal with the other outgoing channels.

EXPERIMENTAL METHOD

The experiments were carried out at the Strasbourg 3 MV Van de Graaff accelerator. The apparatus used to study the (p,α_0) reaction was described in I. An earlier paper[3] gives the method of fabrication of the WO_3 target material and the techniques used for the cleaning of the gold backings and the target preparation for the γ-ray work.

The beam line extension which contained the 200 $\mu g/cm^2$ WO_3 target for these studies also served as a Faraday cup for the scattering chamber during the simultaneous measurements of all the excitation functions. While the yield curve of the (p,α_0) reaction was being observed upstream at four angles from a SiO target, the (p,γ) and $(p,p_1\gamma)$ yields were determined from the downstream WO_3 target by detecting the γ-ray transitions among low-lying ^{18}F levels and the 0.871 MeV transition in ^{17}O with a 54 cm^3 Ge(Li) detector. Correction of the incident energy on the WO_3 target was made for the energy loss in the SiO target. This correction was verified in the subsequent investigation of the radiative capture resonances. Typically the beam intensity was 1μA for for the experiments in which particles were detected. For the γ-ray work (decay schemes, angular distribution) a 6–8 μA beam intensity was used without appreciable target damage.

α-particle angular distributions were measured for the resonances at $E_p = 1784$ and 2095 keV. The analysis was performed in terms of the Biedenharn formalism[4] using the procedure described in Ref. 5. However, because of the number of parameters to be fitted and because of possible uncertainties due to the complexity of the resonance curve, the J^π solutions were less restrictive than those obtained in the analyses of the other exit channels.

The γ-ray angular distribution was measured at five angles with a 120 cm^3 GeLi detector and monitored with one of 54 cm^3. The analysis was performed with a computer code based on the Rose and Brink formalism.[6] To reduce the number of

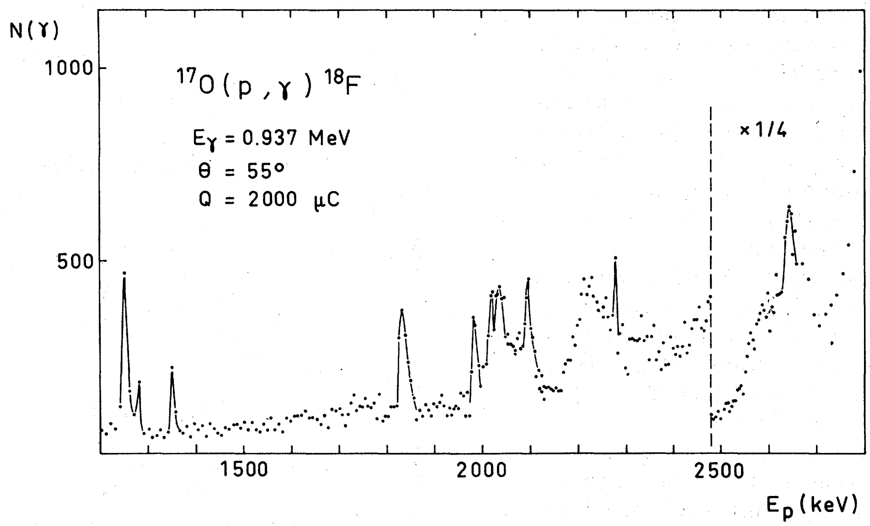

FIG. 1. Excitation function of the ^{17}O (p, γ) ^{18}F reaction for the 0.937 MeV transition.

free parameters in the analysis, the l_p values obtained from the elastic scattering[2] were used to calculate Rose and Brink's B_k parameters for the γ-ray angular distribtuion. The elastic scattering analysis is not very sensitive to small l_p admixtures. The effect of including a 10% admixture of a higher l_p value did not change the result of the γ-ray analysis. The angular distribution attenuation coefficients were calculated taking into account the form and the volume of the detector.

RESULTS

Excitation functions and partial widths

Radiative capture

In the incident energy range $E_p = 1200-2800$ keV, all observed resonances cascade through the first excited state of ^{18}F at 937 keV. The excitation function for this γ-ray is shown in Fig. 1. The lower bombarding energies covered part of the energy region previously studied.[3] The upper energy limit to this excitation curve was imposed by the fact that above $E_p = 2800$ keV, the γ-ray yield from the inelastic scattering became so great that it masked the 937 keV transition. Between $E_p = 1400$ and 1800 keV, there is a slowly increasing yield from direct capture upon which the resonances are superimposed. Off-resonance spectra were taken to determine the direct capture branching ratios so that appropriate corrections could be made to the γ-rays seen in resonant spectra. Our results for the direct capture branching ratios are in good agreement with those of Ref. 7.

In the incident energy range $E_p = 2000-2100$ keV, the narrow resonances are superimposed on both the direct capture background and on broader resonances. Off-resonant spectra were measured to take into account these contributions to the narrow

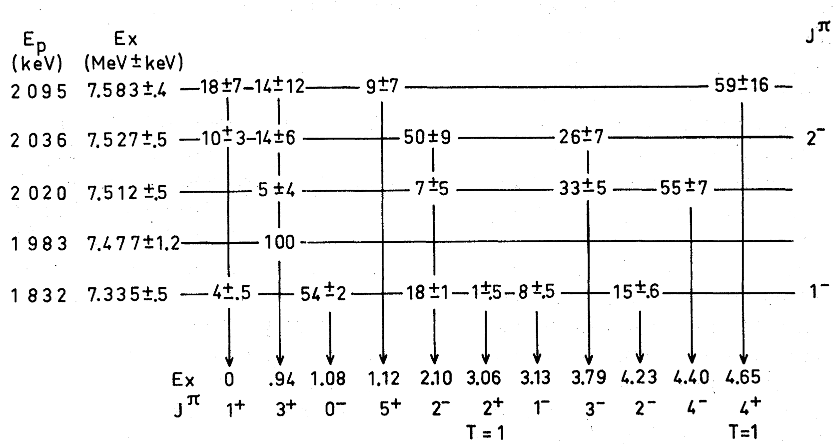

FIG. 2. Decay scheme and branching ratios of the narrow levels observed in the ^{17}O (p, γ) ^{18}F reaction.

resonances but resulted in rather large uncertainties in our reported branching ratios. We therefore do not report angular distribution measurements in this energy range. The decay schemes of the narrow resonant levels are presented in Fig. 2. The branching ratios were deduced from spectra at $\theta = 45°$ with a solid angle $\Omega \simeq \pi$.

The resonance strengths deduced from the excitation function have been determined relative to those of the $E_p = 1101$ and 1245 keV resonances previously studied.[3] The absolute strengths of these two resonances had been determined by comparison with the strength of the ^{27}Al $(p, \gamma)^{28}$Si resonance at $E_p = 655$ keV, for which the value given by Lyons *et al.*[8] was adopted.

From the energy of the γ-ray cascades observed for the five resonances studied, the excitation energies of the corresponding levels are determined in most cases to about ±1 keV or less. The deduced Q values of the ^{17}O(p, γ) ^{18}F reaction is 5604 ± 2.5 keV. This is in good agreement with the previously obtained value of 5603 ± 3 keV (Ref. 3).

(p, α_o) and $(p, p_1\ \gamma)$ reactions

The excitation functions for these two reactions are presented in Fig. 3. Over some parts of the incident energy range for $\Theta_{lab} = 140°$ and 170°, the α-particle peak overlapped the elastically scattered proton peak of silicon. Because of this fact, in approximately one-fourth of the measurements, data were obtained at three angles. In order to remove any angular dependence of the particle from the resonances, the excitation function data measured at four (or three) angles (for the data at 120° see I) were used to calculate, for each incident energy, the A_0 coefficient of a Legendre polynomial expansion limited to order 2. The α-particle yield curve of Fig. 3 is the result of this analysis. This curve, as well as the 871 keV yield curve of the inelastic scattering, was then analyzed in terms of a sum of Breit-Wigner shaped resonances.[9] The angular distribution of the 871 keV γ-rays is isotropic, and an angular dependence correction was not necessary. It must be noted that in some regions, broad asymmetric shapes in both yield curves could not be fitted with the above outlined procedure.

The full lines through the data points (Fig. 3) are the best fits obtained over the entire energy range for each reaction. From these fits the natural widths and strengths of the resonances could be deduced. In most cases the solution of the corresponding equations led to two sets of values for the partial widths Γ_p, Γ_α and $\Gamma_{p'}$. When the magnitude of Γ_p is known from the elastic scattering

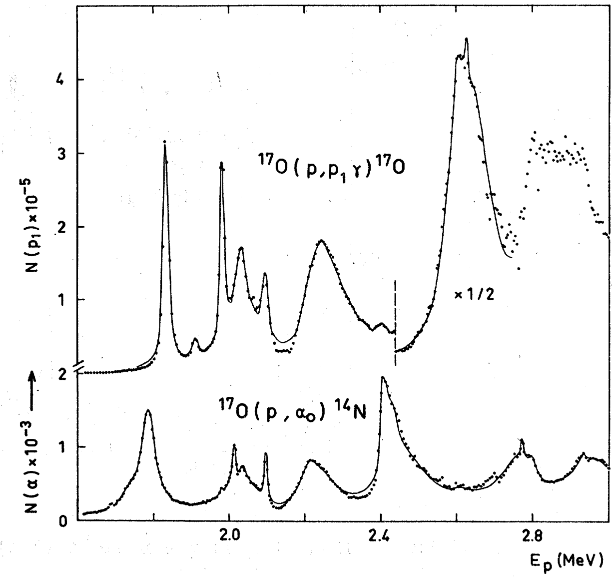

FIG. 3. Excitation functions of the ^{17}O (p, α_0) ^{14}N and ^{17}O $(p, p_1\gamma)$ ^{17}O reactions. The (p, α_0) points are the A_0 obtained from a Legendre polynomial expansion analysis of the angular distributions. The $(p, p_1\gamma)$ points are the yields of 871 keV γ-rays directly. The lines through the data points are the best fits obtained for each curve separately, over the entire energy range, in a Breit-Wigner shape analysis.

analysis, one of these solutions can be eliminated. The Γ_p value obtained in this way may be slightly different from the value obtained in the elastic scattering fit, given in Table I of I.

Resonant levels

In the reactions studied in this work, 25 levels have been observed among which ten have been previously reported. For the most part, the levels treated in I will be omitted from the following discussion.

E_p = 1687, 1738, and 1810 keV resonances

These resonances which correspond to levels at $E_x = 7.198$, 7.245, and 7.313 MeV, respectively, have been observed only in the ^{17}O(p, α_0) ^{14}N reaction. They have previously been reported by several authors[10-13] at $E_x = 7.194$, 7.247, and 7.316 MeV (most accurate excitation energies) with tentative assignments J^π; $T = (4^+)$; 0, (1^+) and $(3^-$; 0), respectively. The total widths found in our work are in agreement with the values given by Herring[11] and Kashy *et al.*[10] From their decay modes by α-particle emission, it can be inferred that all of these states are $T = 0$ and that the positive parity ones have very weak $2p$ components. This is con-

TABLE I. Summary of spectroscopic information obtained in papers I and II.

E_p (keV)	E_x [a] (MeV)	Γ (keV)	J^π [b]	Main decay	Γ_p (keV)	Γ_α (keV)	$\Gamma_{p'}$ (keV)	Γ_γ (eV)	$(2J+1)\Gamma_p\Gamma_\alpha/\Gamma$ (keV)	$(2J+1)\Gamma_p\Gamma_{p'}/\Gamma$ (keV)	$(2J+1)\Gamma_p\Gamma_\gamma/\Gamma$ (eV)
1687.5 ± 1	7.198	6.5	(4^+)	α_0					3.9		
1738 ± 2	7.245	46.5	(1^+)	α_0					8.8		
1784 ± 2	7.289	38	$\underline{3^-}$	α_0, p_0	11.6	22			47		
1810 ± 4	7.313	52	(3^-)	α_0					8.5		
1832.5 ± 1	7.335	16 ± 2	$\underline{1^-}$	p_0, p_1, γ	7		9	3.5 ± 1.0		12	4.7 ± 1.4
1906 ± 2	7.404	14.6 ± 1.4	$\underline{1^+}$	p_0, p_1	12.1		0.6			1.2	
1950 ± 10	7.446	140		α_0					5.6		
1957 ± 2	7.452	6	$\underline{1^-}$	p_0	1						
1983 ± 2	7.477	12 ± 3	(2)	α_0, p_1, γ	2.1	1.7	8.2		1.5	7.2	0.24 ± 0.07
					(10.7)	(0.45)	(2.05)				
(1990 ± 2)	7.483	32	$\underline{(1^-)}$	p_0	5.1						
2012 ± 2	7.504	12 ± 2	$\underline{4^-}$	p_0, α_0	1.2	10	1		7.2	0.7	
2020 ± 2	7.512	< 4		γ							0.22 ± 0.07
2036 ± 2	7.527	16.5 ± 3.0	$\underline{2^-}$	$p_0, p_1, \alpha_0, \gamma$	1.8	8.3	6.4	0.44 ± 0.10	5.5	4.3	0.26 ± 0.06
2040 ± 5	7.531	75		p_1, α_0							
2064 ± 2	7.553	30	(1^-)	p_0	6						
2095 ± 2	7.583	9 ± 2	$\left\langle \underline{1^+} \atop \underline{3\text{–}5^{(+)}} \right\rangle$ [c]	$p_0, \alpha_0, p_1, \gamma$	5.5	2.3	1.8	0.11 ± 0.03	3.7	3.0	0.20 ± 0.06
2202 ± 2	7.684	36 ± 4	$\underline{3^+, 4^+}$ [c]	p_0, α_0, p_1	31	4	1		25.1	6.8	
2248 ± 4	7.727	66 ± 5	$\underline{\geq 1}$	α_0, p_1					28.2	13.4	
2284 ± 4	7.761	70		p_1						29.5	
2406 ± 3	7.876	20	$\underline{\geq 2}$	α_0, p_1					24.4	0.9	
2429 ± 2	7.898	38	(2^-)	α_0					42		
2473 ± 12	7.940	112	(1^+)	α_0					80		
2603 ± 6	8.062	60	$\underline{\geq 4}$	α_0, p_1					11	130	
2657 ± 8	8.113	96		p_1						224	
2757 ± 2	8.208	52	$\underline{2^-}$	p_0, α_0	22	30			63		
2788 ± 2	8.237	20	$\underline{4^+}$	p_0	20						

[a] With $Q = 5.604$ MeV.
[b] The underlined J^π values are from our work including Ref. 2, the others from Ref. 1.
[c] On the assumption of an unresolved doublet.

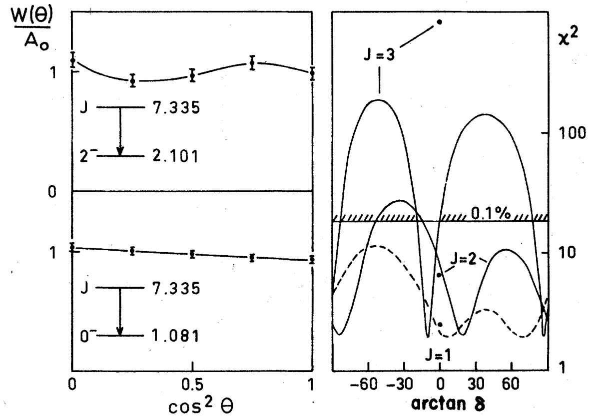

FIG. 4. γ-ray angular distributions for the $E_p = 1832$ keV resonance. The dots are the solutions for the transition to the $J^{\pi} = 0^-$, 1.08 MeV level.

firmed by the weak, or absence of, excitation of these states in the $^{16}O(^3He, p)^{18}F$ reaction.[14]

E_p = 1784 keV resonance

This level at $E_x = 7.289$ MeV level and assigned $J^{\pi} = 3^-$ from the elastic scattering analysis, has a partial width ratio $\Gamma_{\alpha}/\Gamma_p \approx 2$ and a large θ_p^2 (see I). It probably corresponds to the level at 7.26 MeV observed by Middleton *et al.*[13] in the $^{14}N(^7Li, t)^{18}F$ reaction with a large cross section ($\sigma = 2.25$ mb/sr).

E_p = 1832 keV resonance

This level at $E_x = 7.335$ MeV presents a large resonance strength in the (p, γ) reaction. Figure 4 shows the analysis of the angular distribution of the two prominent γ-ray decay lines. On the basis of the odd parity assignment from the elastic scattering analysis, the B_k parameters were calculated for $l_p = 1$ (with and without a 10% $l_p = 3$ admixture) for a channel spin mixing parameter t ranging from 0 to 1. The analysis was also performed with the population parameters as free variables. In both cases, satisfactory solutions were obtained for $J^{\pi} = 1^-$ and 2^- for the two transitions. The value $J^{\pi} = 3^-$, which gives a solution for the transition $R \to 2.10$ MeV, was eliminated by the analysis of the $R \to 1.08$ MeV transition. The transition strengths calculated for the two remaining spin values are listed in Table II. The $R \to 1.08$ transition strength for $J = 2$, $|M|^2(E2) = 51.4$ Weisskopf units (W.u.) is not probable for a self-conjugate nucleus in this mass region. On the other hand, the $|M(M1)|^2 = 0.37$ W.u. strength obtained for $J = 1$ would be too high for a $\Delta T = 0$ transition, but is in agreement with the known distribution of an $M1$, $\Delta T = 1$ transition in self-conjugate nuclei.[15] Although the analysis of the $R \to 2.10$ MeV transition gives a solution for the whole range of δ values, the strengths calculated for the δ's corresponding to the χ^2 minima give $|M(M1)|^2$ values that correspond to a $\Delta T = 1$ transition (Table II). Moreover, the absence of α-particle emission probably indicates an isospin interdiction. The assignment proposed for this level is J^{π}; $T = 1^-$; 1.

E_p = 2036 keV resonance

In the previous paper,[2] this resonance has been proposed $J^{\pi} = 3^-$ on the basis of a better χ^2 in the elastic scattering analysis. Although the uncertainties on the branching ratios are quite large, as already discussed, this spin value would correspond to a transition strength $|M(M2)|^2 = 18 \pm 6$ W.u. for the transition to the ground state. This value is outside the strength distribution,[15] and the spin $J^{\pi} = 2^-$ would give a more realistic result. The observed partial width ratio $\Gamma_{p_1}/\Gamma_p = 4.7$ is also in favor of the 2^- value. If both spin

TABLE II. Transition strengths calculated for the $E_P = 1832$ keV resonance. From data in this table $J = 2$ is rejected.

Transition	$J = 1(\Gamma_\gamma = 3.5 \pm 1.0$ eV)	$J = 2(\Gamma_\gamma = 2.1 \pm 0.6$ eV)
$R \to 0(1^+;0)$	$\|M(E1)\|^2 \le 0.75 \times 10^{-3}$ W.u.	$\|M(E1)\|^2 \le 0.45 \times 10^{-3}$ W.u.
$R \to 1.08(0^-;0)$ [a]	$\|M(M1)\|^2 = 0.37 \pm 0.11$	$\|M(E2)\|^2 = 51.4 \pm 15.4$ ($\delta = 0.34$)
$R \to 2.10(2^-;0)$ [b]	$\|M(M1)\|^2 = 0.21 \pm 0.06$ (for $\delta = 0.1$)	$\|M(M1)\|^2 = 0.12 \pm 0.04$ ($\delta = 0.34$)
	$\|M(E2)\|^2 = 63 \pm 19$ (for $\delta = 2.75$)	$\|M(E2)\|^2 = 4.4 \pm 1.3$ ($\delta = 0.34$)
$R \to 3.06(2^+;1)$	$\|M(E1)\|^2 \le 10^{-3}$	$\|M(E1)\|^2 \le 0.6 \times 10^{-3}$
$R \to 3.13(1^-;0)$	$\|M(M1)\|^2 \le 0.18$	$\|M(M1)\|^2 \le 0.11$
$R \to 4.23((2)^-;0)$	$\|M(M1)\|^2 \le 0.84$	$\|M(M1)\|^2 \le 0.50$

[a] $A_2 = -0.07 \pm 0.02$.
[b] $A_2 = 0.01 \pm 0.06$; $A_4 = 0.12 \pm 0.06$; $A_6 = -0.15 \pm 0.06$.

values are compatible with an $l_p = 1$ orbital momentum for the elastic scattering, $J^\pi = 2^-$ corresponds also to $l_{p_1} = 1$, but $J^\pi = 3^-$ requires an $l_{p_1} = 3$. The penetration factor ratio $P(l_1 = 1)/P(l_1 = 3)$, larger than 200, would strongly disfavor dynamically the inelastic channel if the spin value were $J^\pi = 3^-$. From both arguments we conclude that the assignment of the 7.527 MeV level observed in the (p, γ) channel is $J^\pi = 2^-$. The $M1$ strengths of the transitions 7.527 → 2.10 MeV $[|M(M1)|^2 \leq 0.1$ W.u.$]$ and 7.527 → 3.29 MeV $[|M(M1)|^2 \leq 0.15$ W.u.$]$ correspond to $\Delta t = 1$ transitions. This level can be assigned $T = 1$, with an isospin admixture indicated by the important α-particle partial width. Because of the high level density in this region, it is, however, possible that the resonances reported at the same energy for the (p, p) and (p, γ) channels correspond to a doublet.

E_p = 2095 keV resonance

This level at $E_x = 7.583$ MeV is observed in all outgoing channels. The elastic scattering gives a positive parity and the spin value $J = 1$. On the other hand, the complete γ-ray decay scheme is consistent only with $J = 3$ [and probably a positive parity, because the strong decay to the 4.65 MeV $(4^+; 1)$ level suggests an $M1$, $\Delta T = 1$ transition]. A possible explanation could be the presence of a doublet with one level $J^\pi = 1^+$, accounting for the γ-ray transition to the ground state and to the 0.937 MeV level, the other one having a spin value between 3 and 5 with a positive parity. This hypothesis is supported also by a difference of 2 keV between the (p, α_0) and the (p, γ) resonance energies. This difference, however, cannot be considered significant since it is within the energy uncertainties.

E_p = 2248, 2406, and 2603 keV resonances

These resonances are located in the region where the elastic scattering analysis was not reliable. Spin limitation $J \geq 1$, ≥ 2, and ≥ 4, respectively, can be deduced from the total widths and resonance strengths of the other outgoing channels. The 2406 keV resonance corresponds to the level at 7.876 MeV previously observed at $E_x = 7.877$ MeV in the $^{16}O(^3He, p)^{18}F$ (Refs. 12 and 14) and $^{16}O(\alpha, d)^{18}F$ reactions.[12] The excitation energy is in agreement with the value of Sen Gupta *et al.*,[14] and our spin limitation is consistent with the previous assignment J^π; $T = (2^-)$; 0.

E_p = 2429 and 2473 keV resonances

These levels at $E_x = 7.898$ and 7.940 MeV, observed only in the (p, α_0) channel, are probably the two states reported by Kashy *et al.*[10] at 7.91 and 7.95 MeV, having $J^\pi = (2^-)$ and (1^+), respectively. The total widths are in good agreement with the previous values.

E_p = 2757 keV resonance

This level at $E_x = 8.208$ MeV has been assigned $J^\pi = (1, 2)^-$ from our elastic scattering analysis. On the basis of the resonance strength of the (p, α_0) reaction, solutions are only found for the partial width for $J \geq 2$. Accordingly this state is assigned $J^\pi = 2^-$.

DISCUSSION

Negative parity, $T = 0$ states

The negative parity states below 7 MeV have been described[16,17] by 3p-1h configurations, with some 5p-3h admixtures even in the low-lying states, to obtain the proper excitation energies. At excitations above 7 MeV, $2p$ states $(sd)^1(fp)^1$ are predicted by the shell model, and configurations such as $(1d_{5/2}, 2p_{3/2})$ could be excited in $^{17}O + p$ reactions. If there are such states with rather pure $2p$ configurations they would give rise to prominent peaks in the p channels with almost no α-particle emission.

Another configuration which is expected to lie in this energy region is the 4p-2h $(sd)^3(fp)$ one. Using the weak coupling model suggested by Arima *et al.*,[18] Benson and Flowers,[19] and more recently Sakuda *et al.*,[20] successfully described the deformed even parity states of ^{18}O and ^{18}F by coupling two $(p_{1/2})^{-2}$ holes to the $K^\pi = 0^+$ ground state rotational band of ^{20}Ne. Zuker has shown[21] that this model reproduces the odd parity state properties. A similar procedure, applied to the $K^\pi = 0^-$ band of ^{20}Ne proposed by Nagatani *et al.*[22] to be based on the $J^\pi = 1^-$ state at 5.78 MeV, would lead to a 4p-2h odd parity band $(sd)^3(fp)(p_{1/2})^{-2}$ with the two holes coupled to $J = 1$, $T = 0$. Calculations of Arima and Yoshida[23] and Buck *et al.*[24] have given a satisfactory description of the widths of the 4p state bands in ^{20}Ne and 4p-4h ones in ^{16}O for both parities. Such a calculation has not yet been performed in the case of ^{18}F. The coupling of $(p_{1/2})^{-2}_{J=1, T=0}$ to the ^{20}Ne band leads to triplets in ^{18}F. The widths of these states are expected to have values between the rather narrow ones in ^{20}Ne and the broad ones in ^{16}O, that is, roughly around 100 keV.

Using the Zamick formulation[25] of the Bansal and French idea[26] to calculate the centroids E of the members of the triplets we get

$$E\{(p^{-2})^{T_h}[(sd)^3(fp)]^{T_p}-E(sd)^2\}$$
$$=\mathrm{BE}(^{20}\mathrm{Ne})+E_x-\mathrm{BE}(^{18}\mathrm{F})+\mathrm{BE}(^{14}\mathrm{N})$$
$$-\mathrm{BE}(^{16}\mathrm{O})-8a+\frac{b}{2}[T(T+1)-T_h(T_h+1)$$
$$-T_p(T_p+1)]+E_{cb}$$

with

$$E_{cb}=Nc\langle T_pT_hT_{zp}T_{zh}|TT_z\rangle^2,$$

where the left-hand term is the excitation energy of the centroid, the BE's are binding energies of the nuclei, E_x the excitation energy of the ^{20}NE basis state, T_h and T_p the isospins of the holes and particles, and E_{cb} the Coulomb energy term in which N is the number of proton-proton hole combinations. The constants taken are $a=-0.25$, $b=5$, and $c=-0.5$ MeV. Using Wapstra's mass tables[27] the results are the following for $^{14}\mathrm{N}\otimes{}^{20}\mathrm{Ne}$ ($K^\pi=0^-$):

$$E=-0.315+E_x-8a+2c=E_x+0.685\ \mathrm{MeV}.$$

Thus the centroids of the triplets are calculated to lie at 6.480, 7.820, and 10.945 MeV. No $J^\pi=0^-$ state of ^{18}F can be proposed for the level based on the ^{20}Ne $J^\pi=1^-$ state at 5.79 MeV, but two candidates are known at $E_x=6.646$ and 6.808 MeV, with spins and total widths $J^\pi=1^-$, $\Gamma=89$ keV and $J^\pi=2^-$, $\Gamma=90$ keV, respectively, which are accounted for almost exclusively by the α channel. Among the resonances observed in this work having a definite spin assignment and a large α-particle partial width, the $J^\pi=3^-$ level at 7.289 MeV probably belongs to this family. Although its observed width $\Gamma=38$ keV is somewhat smaller than the values mentioned above, from the magnitude of the cross section in the $^{14}\mathrm{N}(^7\mathrm{Li},t)^{18}\mathrm{F}$ reaction, it seems very likely that this level contains at least a part of the $^{14}\mathrm{N}\otimes{}^{20}\mathrm{Ne}(2^-)$ strength. But the Γ_p width implies appreciable admixtures of 3p-1h and eventually $2p$ configurations. On the other hand, the presence of a neighboring $J^\pi=3^-$ state at 7.31 MeV with a larger Γ_α width supports the hypothesis of a distribution of the strength among several states, and would explain the small Γ value mentioned for the 7.289 MeV state. According to the calculated energy of the centroid of the triplet based on the $J^\pi=2^-$ state of ^{20}Ne, it is probable that some of the resonances with large widths observed in the α-particle channel belong to that band, but the correspondence will be impossible to establish as long as the spin and parity assignments are unknown.

$T=1$ states

The five known levels of ^{18}O between $E_x=6.0$ and 7.2 MeV are listed in Table III, with the more recent J^π values and the proposed dominant configuration.

The level at 6.191 MeV ($J^\pi=1^-$) is dominated by the 3p-1h configuration, and the exact wave function[33] shows that this level is mostly described by the coupling $[^{15}\mathrm{N}\otimes{}^{19}\mathrm{F}(\frac{3}{2},\frac{1}{2})]_{T=1}$. However, some contribution of the $^{15}\mathrm{N}\otimes{}^{19}\mathrm{F}(\frac{1}{2},\frac{1}{2})$ coupling lowers its energy. It is difficult to estimate the position of the analog level in ^{18}F from the Zamick formula because one may only calculate the centroid of the $[^{15}\mathrm{O}\otimes{}^{19}\mathrm{F}(\frac{3}{2},\frac{1}{2})]_{T=1}$ coupling leading to a $J^\pi=1^-$ and 2^- doublet, but the $J^\pi=2^-$ level is strongly mixed with the $J^\pi=2^-$ one coming from the $[^{15}\mathrm{O}\otimes{}^{19}\mathrm{F}(\frac{5}{2},\frac{1}{2})]$ coupling. Among the states observed in this work, we have assigned the 7.335 MeV level to be J^π, $T=1^-$, 1. This state is certainly the analog of the 6.189 MeV level of ^{18}O. It must be noted that, in previous work,[3] we found the negative parity analog states below 7 MeV excitation

TABLE III. Resume of information on the ^{18}O states between 6.0 and 7.2 MeV and their proposed analogs.

		^{18}O				^{18}F				
Exp. E_x (MeV)	J^π_N	Ref.	Calc. E_x (MeV)	Configuration (Ref. 32) 3p-1h	5p-3h	Calc. E_x (MeV)	Configuration (Ref. 33) 3p-1h	5p-3h	Proposed analog E_x (MeV)	Weak coupling configuration
6.201	1^-_2	28–30	6.61	76%	24%	7.01	55%	45%	7.335	$^{15}\mathrm{O}\otimes{}^{19}\mathrm{F}(\frac{3}{2},\frac{1}{2})$
6.351	(2^-_2)	29–31	6.57	73%	27%	6.54	60%	40%	7.527	$^{15}\mathrm{O}\otimes{}^{19}\mathrm{F}(\frac{5}{2},\frac{1}{2})$ $^{15}\mathrm{O}\otimes{}^{19}\mathrm{F}(\frac{3}{2},\frac{1}{2})$
6.404	3^-_2	30	6.25	93%	7%	7.02	45%	55%		$^{15}\mathrm{O}\otimes{}^{19}\mathrm{F}(\frac{5}{2},\frac{1}{2})$
6.882	0^-_1	28	5.91	99.6%	0.4%	7.16	80%	20%		$^{15}\mathrm{O}\otimes{}^{19}\mathrm{F}(\frac{1}{2},\frac{1}{2})$
7.117	4^+_2	34–36	7.21	5% $(2p)$	95% $(4p-2h)$	8.35 9.44	$4p-2h$ [a] pure $d_{5/2}d_{3/2}$ [b]		8.237	$^{14}\mathrm{O}\otimes{}^{20}\mathrm{Ne}$ (70%) $^{16}\mathrm{O}\otimes{}^{18}\mathrm{O}$ (30%)

[a] Space not including $d_{3/2}$.

[b] The state at 9.44 MeV comes from a simple $(sd)^2$ calculation with Kuo-Brown matrix elements. It will mix with the 4p - 2h level at 8.35 MeV of Ref. 33.

energy to be isospin mixed. The absence of α-particle emission from the 7.335 MeV level is taken as evidence for its isospin purity.

The ^{18}O level at 6.341 MeV does not have a definite J^π assignment On the basis of the lifetime limit, Olness *et al.*[31] restrict the spin value to $J \leq 3$, and unnatural parity is suggested by Ollerhead *et al.*[29] The probable J^π value[31] is 1^+ or 2^-. The 6.391 MeV level has been assigned $J^\pi = 3^-$ by Berant *et al.*[30] The "exact" wave function calculated in the $p_{1/2}d_{5/2}s_{1/2}$ configuration space show that the analog states in ^{18}F can be described in the weak coupling scheme by $^{15}\mathrm{O} \otimes {}^{19}\mathrm{F}(\frac{5}{2}, \frac{1}{2})$. Neglecting the possible admixture of $^{15}\mathrm{O} \otimes {}^{19}\mathrm{F}(\frac{3}{2}, \frac{1}{2})$ in the 2^- state and $^{15}\mathrm{O} \otimes {}^{19}\mathrm{F}(\frac{7}{2}, \frac{1}{2})$ in the 3^- one, the Zamick formula gives a centroid of this doublet at $E \simeq 7.43$ MeV. In the previous section, we have shown the 7.527 MeV level of ^{18}F to be isospin mixed, and that state could be the analog of the 6.341 MeV level of ^{18}O, if the hypothesis $J^\pi = 2^-$ is confirmed for this level. One of the various $J^\pi = 3^-$ states observed in this work is probably the analog of the ^{18}O level at 6.391 MeV, but no evidence of a $T = 1$ character was obtained.

The next higher state of the experimental ^{18}O spectrum has been discussed by several authors.[28,31] Among the remaining possible J^π values (0^- and 1^+), the $J = 0$ is favored from the observed γ-ray decay mode.[28] It would be the first $J^\pi = 0^-$ level of the spectrum. The analog state in the ^{18}F spectrum can be described by the $[^{15}\mathrm{O} \otimes {}^{19}\mathrm{F}(\frac{1}{2}, \frac{1}{2})]_{T=1}$ coupling, which leads to a J^π

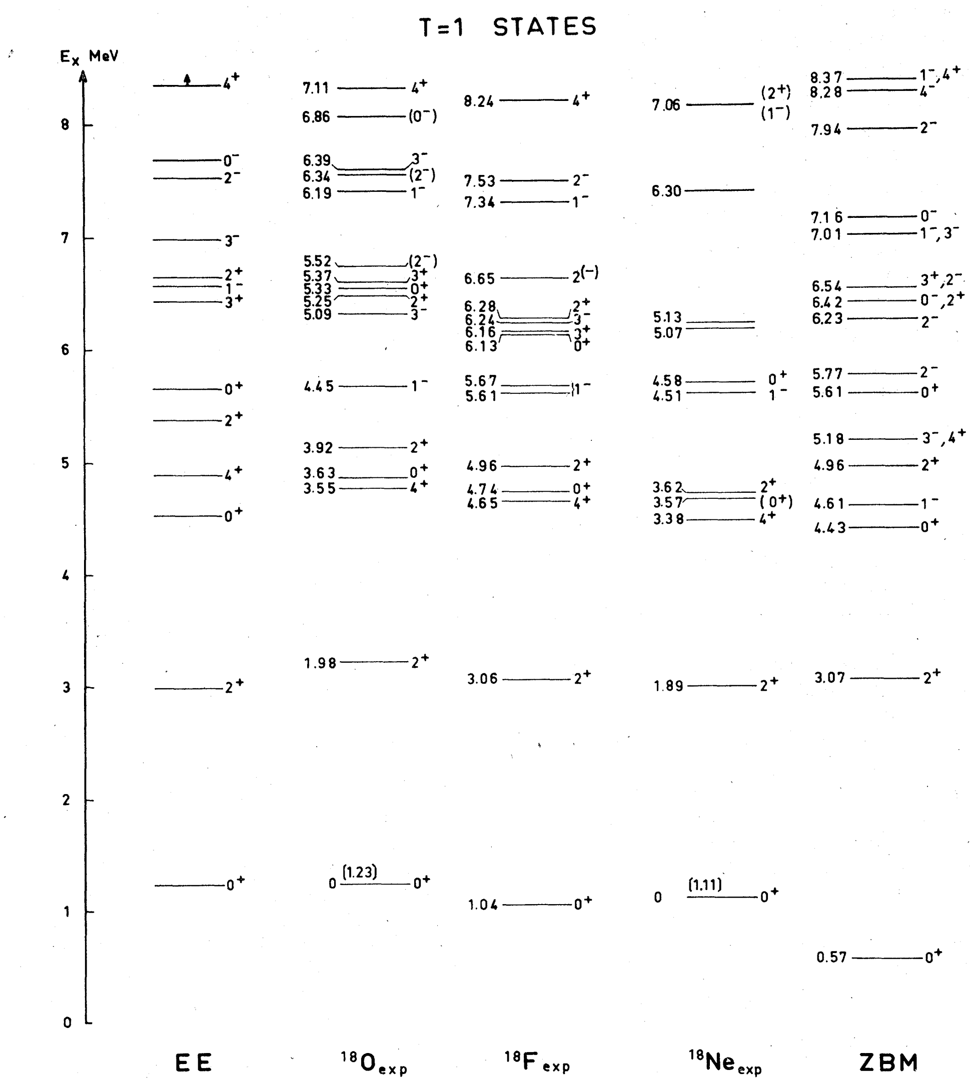

FIG. 5. Experimental and calculated spectra of $T = 1$ states for the $A = 18$ triplet. *EE* is Ellis and Engeland (Ref. 17) and ZBM is Zuker, Buck, and McGrory (Ref. 16) and Zuker (Ref. 21).

$=0^-$ and 1^- doublet. The $J^\pi=1^-$ member of this doublet is found experimentally at $E_x=5.6$ MeV and is strongly mixed with a J^π, $T=1^-$, 0 state. On the basis of the centroid value of the doublet $E=7.2$ MeV, calculated by the weak coupling formula, the 0^- member would lie at an excitation energy $E_x \sim 8.7$ MeV. In view of the reasonable energies obtained in the shell-model calculations, this example seems to demand some caution in using naively the weak coupling picture for energy assignments. If the calculation of the wave function by the weak coupling method appears to be accurate enough, the energy calculation cannot take into account the core polarization of the coupled states. In the present case, the $\sim 20\%$ 5p-3h admixture may decrease the excitation energy of the 0^- state by more than 1 MeV.

The fifth known level of ^{18}O in the range of interest is the $J^\pi=4^+$ state at 7.12 MeV. Many experimental studies have established the properties of this level. From a plane-wave Born approximation analysis of the $^{17}O(d,p)$ ^{18}O reaction, Wiza *et al.*[34] have shown that this level has an appreciable $2p(d_{5/2}d_{3/2})$ component, and the weak coupling calculation of Ellis and Engeland[17] gives a 4p – 2h strength of about 70%. This result is in agreement with the experimental data from the $^{14}C(\alpha,\gamma)^{18}O$ reaction[35] and $^{14}C(^7Li,t)$ reaction[36] and the distorted-wave Born approximation calculation of Li *et al.*[37]

The only $J^\pi=4^+$ state observed in our work is the 8.237 MeV level.[2] On the basis of this assignment and of the observed spectroscopic factor, we conclude that this level is the analog of the 7.12 MeV level of ^{18}O. This hypothesis is also supported by the absence of α-particle emission, which can only be explained by an isospin inhibition. Our single particle spectroscopic factor $S=0.3$ is consistent with a large 4p-2h component of the wave function.

In the calculated 2p spectrum,[33] the $4^+(d_{5/2},\ d_{3/2})$ state is obtained at $E_x=9.44$ MeV, and obviously the 8.237 MeV level carries only a fragment of the $(d_{5/2}d_{3/2})$ strength which is in turn strongly mixed with the pure 4p-2h state calculated to lie at 8.35 MeV (see footnote in Table III concerning this state). The remaining fragment of the 2p strength will probably be found between 9 and 10 MeV excitation energy. The last column of Table III presents the weak coupling configurations proposed for the $T=1$ states of ^{18}F and Fig. 5 shows the experimental $T=1$ spectrum for the $A=18$ triad, together with the calculated spectra of Refs. 16 and 17.

ACKNOWLEDGMENTS

The authors wish to thank A. P. Zuker for helpful discussions concerning this work and J. P. Weymann for assistance in some aspects of the experimental set up. One author (S. M. R.) would like to thank Professor R. Armbruster for his hospitality and interest in this work. He is also grateful to the French Government for providing a fellowship.

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