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Search for simple configurations in ^{18}F. I. The ^{17}O(p,p)^{17}O reaction

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The ^{17}O(p,p) ^{17}O reaction has been studied in the energy range E_p =1.4–3.0 MeV. An R matrix analysis of the elastic scattering excitation functions at four angles leads to l_p values for 12 resonances. Some J^{π} assignments have been made. States with large $d_{5/2}d_{3/2}$ configurations have been located at: 7.404 ($J^{\pi}=1^+$), 7.683 [$J^{\pi}=(3)^+$], and 8.237 ($J^{\pi}=4^+$) MeV.

[NUCLEAR REACTION ^{17}O(p,p), E=1.4–3.0 MeV; measured $\sigma(E_p, \theta)$. ^{18}F levels deduced l_p, J^{π}, Γ_p. Enriched target.]

INTRODUCTION

Because of their theoretical interest for testing shell model calculations, the $A=18$ nuclei and especially the ^{18}F nucleus, in which almost two hundred levels are reported,[1] are among the most thoroughly investigated. However, if experimental and theoretical studies have led to a good understanding of excited states up to 7 MeV, most of the data on higher levels are provided by (α,α) and (α,d) reactions and, for instance, the distribution of the $2p(d_{5/2},d_{3/2})$ strength remains unknown. In previous work[2] we found a $J^{\pi}=4^+$ state at 6.78 MeV which has been suggested as dominated by this configuration. It is of interest to extend the existing work on proton induced reactions on ^{17}O, limited to $E_p=1.4$ MeV ($E_x \approx 6.9$ MeV, Ref. 2) to higher energies, because from theoretical considerations one expects to observe most of the $d_{5/2}d_{3/2}$ levels as well as $2p$ negative parity states ($d_{5/2}f_{7/2}$ or $d_{5/2}2p_{3/2}$) between 7 and 9 MeV excitation. In this work, we have observed all the exit channels corresponding to the ^{17}O+p entrance channel, in the energy range E_p=1.4–3.0 MeV. The present paper deals primarily with the elastic scattering and another paper, referred to as II, will present data on the other exit channels.

EXPERIMENTAL METHOD

The first part of the experiment, performed with the Strasbourg 3 MV Van de Graaff accelerator, consisted in the simultaneous measurement of the excitation functions for the ^{17}O(p,p)^{17}O and ^{17}O(p,α_0)^{14}N reactions with a 45 μg/cm^2 enriched self-supporting SiO target, and the γ-ray yields of the ^{17}O(p,γ)^{18}F and ^{17}O($p,p_1\gamma$)^{17}O reactions from an enriched WO$_3$ target located in the Faraday cup of the scattering chamber downstream from the SiO target. Details concerning the γ-ray part of the experiment will be given in II.

The particles were detected by four Si surface barrier detectors placed at backward angles. The target-counter distance and the collimator sizes were adjusted to give comparable counting rates at each angle. Data were accumulated in a Multi-20 Intertechnique on-line computer.

The accelerator calibration was obtained to ±1.5 keV with the ^{27}Al(p,γ)^{28}Si and ^{13}C(p,γ)^{14}N reactions at the 991.90 and 1747.6 keV resonances.[3] The intrinsic beam straggling [full width at half maximum (FWHM)], measured with a thick aluminum target at the above stated resonance, was 350 eV. The experimental straggling including the effect of the SiO target thickness was about 3 keV for 1 MeV protons. An $E^{-1/2}$ energy dependence for the straggling was assumed.

ANALYSIS AND RESULTS

Figure 1 shows the elastic scattering excitation functions at four angles, as well as the ^{17}O(p,α_0)^{14}N yield curve at $\theta_{\text{lab}}=120°$. In the energy range covered, the ^{16}O(p,p)^{16}O scattering presents a single strong resonance at E_p= 2.66 MeV. A large number of anomalies in the ^{18}O(p,p)^{18}O scattering are also known.[1] However, with the detector energy resolution ranging between 12 and 16 keV, the peaks of the three oxygen isotopes were resolved well enough at the most backward angles over the entire energy range as shown in Fig. 2. At 90° and 120°, the peaks were not completely resolved, and the uncertainty in peak fitting was larger. Over parts of the incident energy range, the α-particle peak from the ^{17}O(p,α_0)^{14}N reaction overlapped the elastically scattered proton peak from silicon. Thus for θ_{lab} = 140° and 170°, part of the α-particle yield function could not be obtained for these angles. The

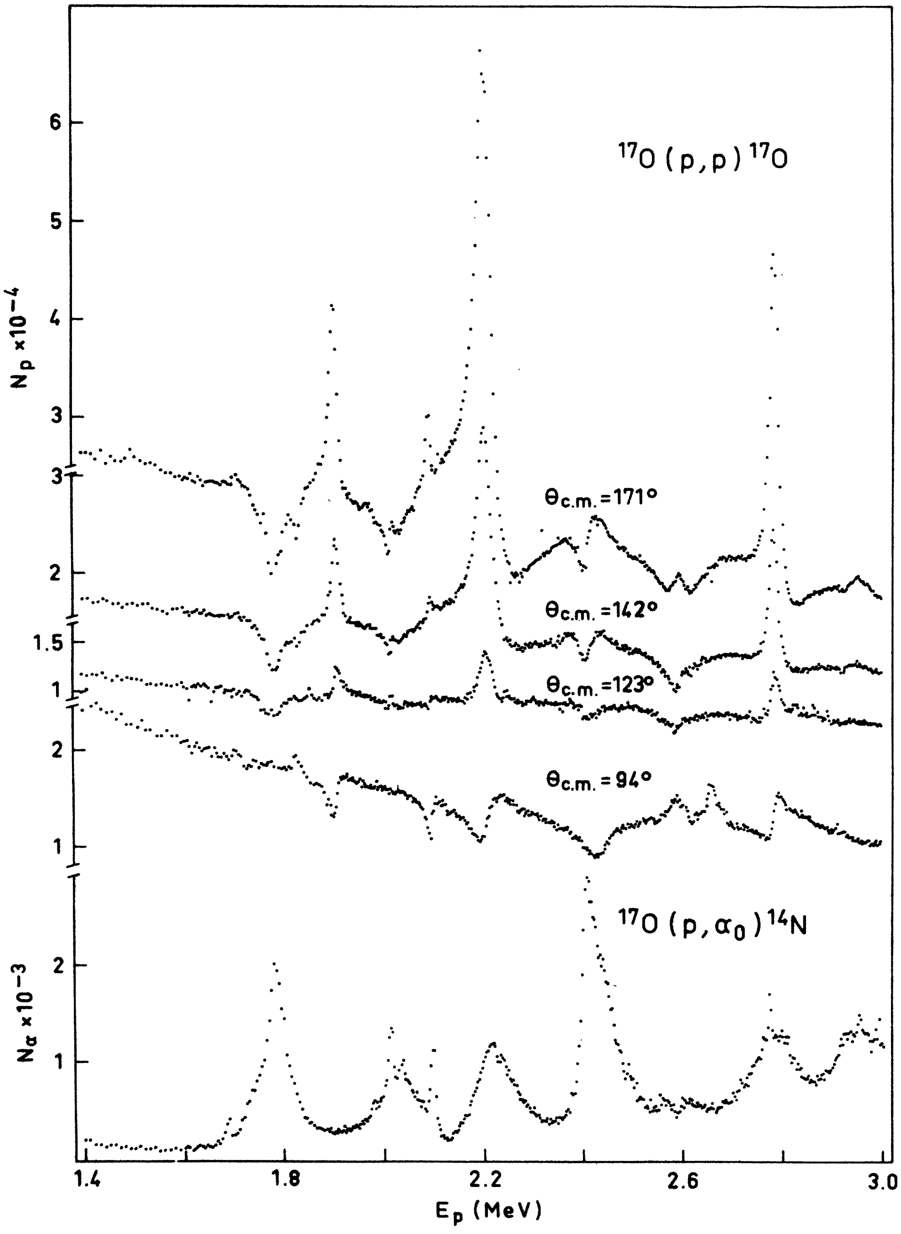

FIG. 1. Excitation functions of the $^{17}O(p,p)^{17}O$ reaction at four angles and of the $^{17}O(p,\alpha_0)^{14}N$ reaction at $\theta_{lab}=120°$.

data were analyzed with an elastic scattering program using the Blatt and Biedenharn formalism.[4] This program can handle up to six resonances, with the resonance energy, the total and partial width for each channel spin, and the l_p admixtures compatible with the assumed J^π values of the levels as fitted parameters. The calculated cross sections were weighted to take into account the effect of the beam straggling on the shape and amplitude of the observed anomalies. The energy distribution of the beam was taken as a triangular function with an area normalized to unity, the projections of the high and low energy side on the base being twice the intrinsic and experimental straggle, respectively. Figures 3 and 4 show the best fits obtained in the energy range $E_p = 1.7-2.3$ MeV and around $E_p = 2.8$ MeV. The analysis was mostly based on the 170° data, but good agreement was always obtained for all the angles of observation.

In the energy range $E_p = 2.4$ to 2.7 MeV, attempts to fit the data for all the angles simultaneously failed, presumably because of the many overlapping resonances. No characteristic elastic scattering shape was observed.

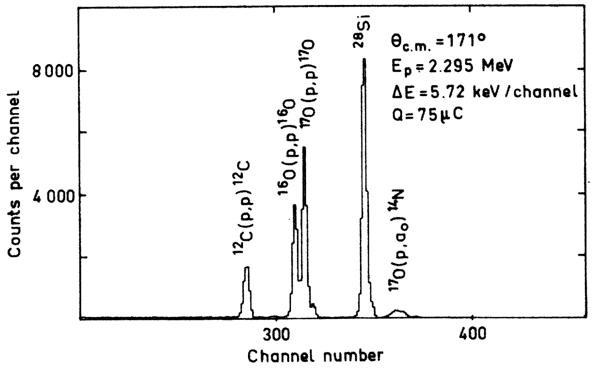

FIG. 2. Particle spectrum at $E_p = 2.295$ MeV and $\theta_{c.m.} = 171°$.

Although the l_p values could be determined unambiguously for the 12 analyzed resonances, several J^π values could sometimes give a satisfactory fit, each with a different set of total and proton widths. From the analysis of the (p, α_0) and $(p, p_1\gamma)$ yield curves, it was possible to obtain the quantities $(2J+1)\Gamma_p\Gamma_{\alpha_0}/\Gamma$ and $(2J+1)\Gamma_p\Gamma_{p_1}/\Gamma$ (to be discussed in II) and to restrict the possible J^π values on the basis of the required proton width.

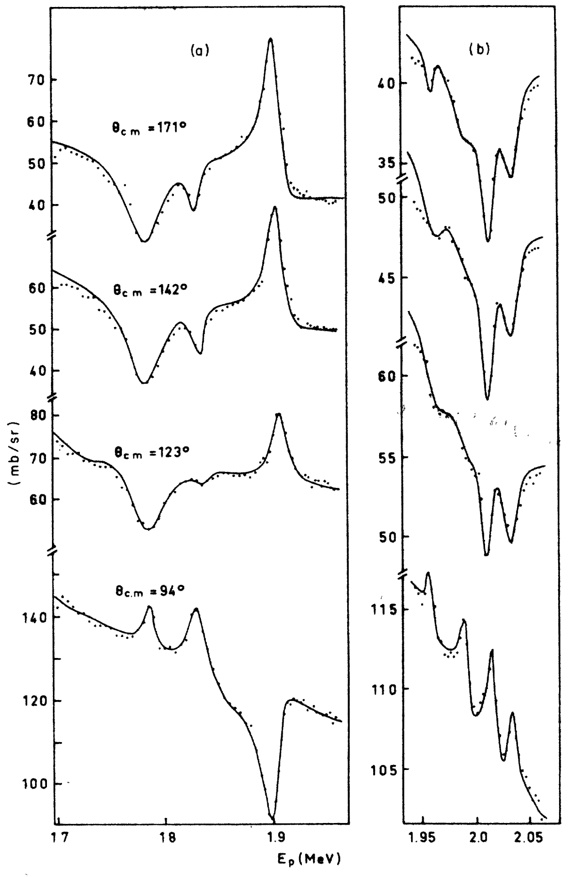

FIG. 3. Analysis of the elastic scattering excitation functions between $E_p = 1.7$ and 2.1 MeV. The full lines through the points are best fits from R-matrix theory made separately for each angle over the energy range given by the respective abscissas.

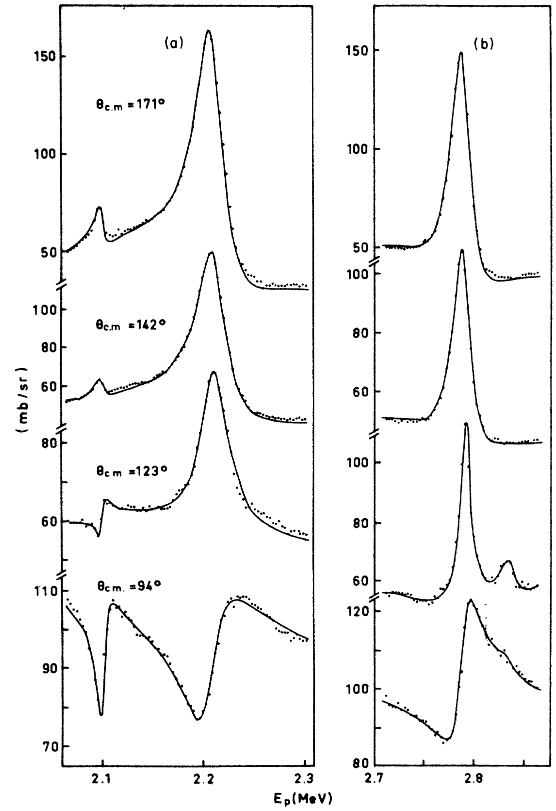

FIG. 4. Same as for Fig. 3, for $E_p = 2.05$ to 2.3 MeV and around $E_p = 2.8$ MeV.

1784, 1832, and 1906 keV resonances

These states can be described only by $l_p = 1$ for the first two and $l_p = 2$ for the third [see Fig. 3(a)]. The best fit was obtained for $J^\pi = 3^-$, 1^-, and 1^+, respectively. The corresponding levels have not been reported previously, and it seems that the $J^\pi = 3^-$, 7.30 MeV level observed by Kashy *et al.*[5] in the ^{14}N$(\alpha, \alpha)^{14}$N reaction corresponds to the 1810 keV resonance observed in the ^{17}O$(p, \alpha_0)^{14}$N reaction (see II) and not to the 1784 keV resonance.

1957, 1990, 2012, and 2036 keV resonances

These are all characterized by $l_p = 1$ [see Fig. 3(b)], and the proposed J^π values are listed in Table I. A resonance has been reported[6] at $E_p = 2021$ keV in the reaction ^{17}O$(p, \alpha_0)^{14}$N with a width $\Gamma = 11$ keV. It probably corresponds to our resonance at $E_p = 2012$ keV. An anomaly has been ob-

TABLE I. Summary of spectroscopic information obtained in this work.

E_p (keV)	E_x[a] (MeV)	l_p	J^π	Γ (keV)	Γ_p (keV)	$\theta_p^2 \times 10^3$[b]	θ_p^2/θ_p^2 (6.16)	S[c]
1784 ± 2	7.289	1	3^-	38	11.6	9.5	0.07	0.24(1*p*) 0.37(2*p*)
1832 ± 2	7.335	1	$(1,2)^-$	11	7[d]	6[d]	0.04	0.15(1) 0.23(2)
1906 ± 2	7.404	2	1^+	15	12.1	46	0.33	0.70
1957 ± 2	7.452	1	1^-	6	1	0.5	0.004	0.01(1) 0.02(2)
(1990 ± 2)	7.483							
2012 ± 2	7.504	1	4^-	12	1.2	0.7	0.005	0.02(1) 0.03(2)
2036 ± 2	7.527	1	3^-	16.5	1.8	1.1	0.008	0.03(1) 0.05(2)
2064 ± 2	7.553	1	1^-	30	6	3.5	0.025	0.09(1) 0.14(2)
2095 ± 2	7.583	2	1^+	9	5.5	14.8	0.11	0.2
2202 ± 2	7.684	2	$(3,4)^+$	36	32[e]	73[e]	0.52	1
2757 ± 2	8.208	1	$(1,2)^-$	52	22[d]	7[d]	0.05	0.19(1) 0.29(2)
2788 ± 2	8.237	2	4^+	20	20	22	0.16	0.32

[a] With $Q = 5.604$ MeV (see II).

[b] Defined by $\theta_p^2 = \Gamma_p/2P_l W$ where P_l is the penetration factor and W the Wigner limit $3\hbar^2/2\mu R^2$ with $R = 1.4(A^{1/3}+1)$ fm.

[c] Using $\theta_0^2(2s) = 0.15$, $\theta_0^2(1p) = 0.04$, $\theta_0^2(1d) = 0.07$, and $\theta_0^2(2p) = 0.026$. The values labeled (1) and (2) were obtained for $1p$ and $2p$ shells, respectively.

[d] Calculated for $J^\pi = 1^-$.

[e] Calculated for $J^\pi = 3^+$.

served[5] in the α-particle elastic scattering on ^{14}N, corresponding to a $J^\pi = (3^-)$ level at $E_x = 7.52$ MeV. It could correspond to the $E_p = 2036$ keV resonance, whose J^π value is found to be 3^-, but we find a total width $\Gamma = 16.5$ keV instead of the 35 keV previously observed. It must be pointed out that the resonance at $E_p = 1990$ keV could not be fitted with the same total width at all angles, and that the proton width Γ_p is substantially smaller than Γ. This resonance is not observed in the other outgoing channels. Accordingly, no spin assignment is proposed for this level. On the other hand, the shape of the excitation functions at the four angles as well as the quality of the fit (χ^2 improved by a factor 4) with inclusion of this level are taken as evidence of the existence of a resonance at this energy.

2064, 2095, and 2202 keV resonances

These data are shown in Fig. 4(a). The $E_p = 2064$ keV resonance, $l_p = 1$, is not observed in the other outgoing channels, and the proton width deduced from the fit is only 20% of the total width for the smallest J^π value (1^-). The $E_p = 2095$ and 2202 keV resonances can only be fitted by $l_p = 2$. A unique J^π value could be assigned to the former ($J^\pi = 1^+$) but the latter gives equivalent fits for $J = 3$ and 4.

2757 and 2788 keV resonances

These data are fitted by $l_p = 1$ ($J^\pi = 1^-, 2^-$) and $l_p = 2$ ($J^\pi = 4^+$), respectively [see Fig. 4(b)]. An anomaly appears at $E_p = 2835$ keV at $\theta_{\rm lab} = 120°$, and could also be present at 90°, but the parameters required to improve the fit for those angles do not give an acceptable result for the most backward angles. In the energy range between $E_p = 2.4$ and 2.7 MeV, some complicated structure appears that could not be fitted, but resonances are more clearly observed in other channels.

DISCUSSION

Partial widths

The reduced partial widths can in principle be evaluated in terms of spectroscopic factors[7,8] but the estimation of the absolute single particle reduced width θ_0^2 depends on a number of model assumptions and, according to the systematics of Macfarlane and French,[8] depends also on the Q value of the reaction. However, it is possible to use this information at least in a qualitative way by choosing an appropriate reference: In the case of ^{18}F, it may be considered that the $(J^\pi; T) = (3^+; 1)$ state at 6.16 MeV has a spectroscopic factor very close to unity. This state has been considered as almost pure $d_{5/2}s_{1/2}$. In fact if Zuker's wave function[9] gives only an amplitude of 0.76 for this component, the overlap between this wave function and the coupling of a $2s_{1/2}$ proton to the ^{17}O(g.s.) wave function is 0.96. On the other hand, the reduced width obtained from our previous elastic scattering work,[2] is $\theta_p^2 = 0.14$ of the Wigner limit, and Macfarlane and French[8] give a value of the single particle reduced width $\theta_0^2(2s) \approx 0.15$ for nuclei around mass 18.

The spectroscopic factor S defined by $\theta_p^2 = S\theta_0^2$ should be accordingly close to unity for this state. It is now possible to estimate roughly the magnitude of the spectroscopic factors for $l_p \neq 0$ by using the average values of θ_0^2 for the various shells given in Ref. 8. These estimates are presented in the last column of Table I and the considerations that can be deduced for some of the levels are discussed in the following sections.

Positive parity states

In the analyzed region, four resonances are described by $l_p = 2$ angular momenta, three of them having a large reduced partial width. Accordingly, the wave functions of the corresponding states are supposed to present a strong d^2 component. The ^{17}O(g.s.) wave function is given essentially by the coupling of a $d_{5/2}$ neutron to the ^{16}O(g.s.) which presents about 30% of 2p-2h configurations.[9] Accordingly, the d^2 configuration which may contribute is $d_{5/2}d_{3/2}$.

7.404 MeV level

This $J^\pi = 1^+$ state has a reduced proton width of 10% and decays mostly by proton emission to the ^{17}O(g.s.), with a weak decay to the first excited state of ^{17}O($J^\pi = \frac{1}{2}^+$) and no observable α-particle emission. These two latter channels would be dynamically favored because they would proceed through a $l_p = 0$ transition. By assuming the single particle reduced width $\theta_0^2(1d) = 0.07$ (Ref. 8), the spectroscopic factor is $S \approx 0.7$. The $2p$ character of this level is strongly suggested by this value and by the absence of α-particle emission. An isospin inhibition is improbable because the first $(J^\pi; T) = (1^+; 1)$ state is expected to occur at $E_x \approx 10$ MeV. On the other hand, the weakness of the inelastic channel shows that the $(2s_{1/2})^2$ component of this state is also very weak. Among the known $(J^\pi; T) = (1^+; 0)$ states in ^{18}F, the ground state is described by a strong admixture of $(d_{5/2})^2$ and $d_{5/2}d_{3/2}$ configurations.[10] The 1.70 MeV level has a dominant 4p-2h configuration.[11,12] The 3.72 MeV level suggested by Rolfs *et al.*[13] as a $2p$ state has been shown by Millener[12] to contain an appreciable 4p-2h component. This conclusion is supported by a recent study of the ^{16}O(^{3}He, p)^{18}F reaction[14] in which this state gives a poor $2p$ fit with a distorted wave Born approximation (DWBA) analysis. The fourth level at 6.27 MeV has been observed only in ^{14}N + α scattering.[15]

This new level at $E_x = 7.404$ MeV seems to be the first $(J^\pi; T) = (1^+; 0)$ d^2 state to carry a large part of the $d_{5/2}d_{3/2}$ strength. Its position is in good agreement with the prediction of shell model calculations.[16]

7.583 MeV level

This level has a rather important α-particle width (see II), indicating a $T = 0$ character as well as the presence of 4p-2h components in the wave function. From the approximate spectroscopic factor $S_p = 0.2$, the $2p$ components are weaker. This level could correspond to the $J^\pi = 1^+$ state predicted by the weak coupling scheme as resulting from the coupling of $(p_{1/2})^{-2}$ to the 6.7 MeV level ($J^\pi = 0^+$) of ^{20}Ne.

7.684 and 8.237 MeV levels

These levels having J^π values 3^+ or 4^+ show an important proton width and weak α-particle emission. The experimental spectrum of ^{18}F presents at least five states $(J^\pi; T) = (3^+; 0)$ below $E_x = 7$ MeV, two of them being considered as admixtures of $d_{5/2}{}^2$ and $d_{5/2}s_{1/2}$ ($E_x = 0.937$ and 4.12 MeV), the others being 4p-2h ($E_x = 3.35$, 6.31, and 6.48 MeV). Among the known $J^\pi = 4^+$ states, the 5.30 MeV level has a 4p-2h configuration; very little spectroscopic information is known about the 5.60 MeV level whose spin assignment is not definite; and the $E_x = 6.78$ MeV, $T = 0$ level is mostly $d_{5/2}d_{3/2}$, the partial proton width $\theta_p^2 = 0.062$ observed by proton elastic scattering corresponding to a spectroscopic factor $S_p \approx 0.9$.

The $T = 1$ state at $E_x = 4.65$ MeV is $d_{5/2}{}^2$. From our proton partial width, the spectroscopic factors for the 7.684 and 8.237 MeV levels are ≈1 and 0.32, respectively, supporting the assumption of an almost pure $d_{3/2} \otimes {}^{17}$O(g.s.) configuration for the former, and an appreciable admixture of $d_{5/2}d_{3/2}$ and 4p-2h for the latter. In the ^{16}O(^{3}He, p)^{18}F reaction, Sen Gupta *et al.*[14] have obtained a satisfactory DWBA fit for the 8.237 MeV level with a $d_{5/2}d_{3/2}$ wave function, but their observed cross section is much smaller than the cross sections measured for the other $2p$ $J^\pi = 4^+$ states. This may indicate that our spectroscopic factor could be underestimated, but supports the presence of strong 4p-2h components. It is somewhat surprising that the 7.684 MeV level, which appears from this work to have a much more important $2p$ configuration, is not observed in the ^{16}O(^{3}He, p)^{18}F reaction.[14] Because only three $2p$ states with $J^\pi = 4^+$ are predicted by the shell model, with configurations $d_{5/2}^2$ (with $T=1$) or $d_{5/2}d_{3/2}$ $(T=0,1)$, it seems plausible that the spin of the level at $E_x=7.684$ MeV is $J=3$, since the assignment for the 8.237 MeV level is $J^\pi=4^+$.

The ^{18}O spectrum presents a $J^\pi=4^+$ level at 7.11 MeV.[1] It seems very likely that the analog of this state in ^{18}F is the 8.237 MeV level, which is the only $J^\pi=4^+$ state observed in this work. A discussion on analog states will be given in II.

Negative parity states

It has been shown[17,18] that the negative parity states below an excitation energy of 7 MeV are predominantly 3p-1h with some 5p-3h admixtures. These states are excited weakly in the ^{17}O$+p$ reaction through the 20% 3p-2h component of the ^{17}O(g.s.) wave function. At energies above 7 MeV, the shell model predicts the existence of $2p$ states with $(sd)(fp)$ configurations. A configuration like $1d_{5/2}2p_{3/2}$ could be formed through the major component of the ^{17}O(g.s.) wave function. Some of the negative parity states observed in this work probably belong to this category, but with all of them showing an α-particle emission (see II), they would seem to be mixed with 3p-1h or 4p-2h $(sd)^3(fp)(p_{1/2})^{-2}$ configurations.

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