$^{17}O(^3He,d)^{18}F$ reaction and its implication in the ^{17}O destruction in the CNO cycle in stars

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The proton stripping reaction $^{17}O(^3He,d)^{18}F$ has been used to reinvestigate the proton widths of the states in ^{18}F near the proton threshold. Distorted-wave angular distributions were calculated using appropriate methods for stripping to unbound states. The deduced proton width for the level at $E_x = 5.673$ MeV ($J^\pi = 1^-$) is significantly larger than a previous value obtained from a direct radiative capture experiment. A subthreshold state at $E_x = 5.603$ MeV ($J^\pi = 1^+$) was found to have a rather large proton reduced width so that this state contributes significantly to the astrophysical S factor at low energy. These measurements lead to substantial changes in the stellar reaction rate for the $^{17}O(p,\alpha)^{14}N$ reaction. This result is discussed in relation to recent observation of the isotopic abundance ratio $^{16}O/^{17}O$ in red giant stars. In addition, the nuclear structure of ^{18}F is studied via the measurement of spectroscopic factors for most of the levels in ^{18}F bound against proton decay.

I. INTRODUCTION

In stars where temperature can exceed about 18×10^6 K, material is highly processed by the sequence of reactions of the so-called carbon-nitrogen-oxygen (CNO) cycle. This cycle of reactions is responsible for the synthesis of ^{14}N and of some of the carbon and oxygen isotopes, such as ^{13}C and ^{17}O. Cross sections of the proton induced reactions in the CNO cycle have been extensively studied during the last few years, but large uncertainties remain in the values of reactions rates needed for understanding nucleosynthesis in stars during their hydrogen burning phase. For the specific case of the reactions $^{17}O(p,\alpha)^{14}N$ and $^{17}O(p,\gamma)^{18}F$ destroying ^{17}O, there are no direct experimental data[1] below 400 keV.

Standard descriptions of the evolution of stars on the first ascent to the red giant branch predict that the convective envelope will bring to the surface material processed by CNO-cycle nuclear reactions during the preceding main-sequence evolution. Observations of the $^{16}O/^{17}O$ ratio in such stars may thus provide much information on the amount and depth of mixing due either to the first dredge-up process or to slow mixing during the main-sequence phase.[2] Observations of the oxygen isotopic abundances in the atmospheres of several evolved stars have been recently reported.[2-7] In a variety of stars assumed to be ascending the red giant branch, the $^{16}O/^{17}O$ ratios were found to range from 1100 to 160 (Ref. 3), thus revealing an important enrichment in ^{17}O relative to the solar value of 2485 (Ref. 8). In contrast, in more evolved *MS*-, *S*-, and *N*-type carbon stars,[5,7] the $^{16}O/^{17}O$ ratios were found to be larger than expected from theoretical models of stars on the asymptotic giant branch (AGB stars). Unfortunately, the interpretation of all these observations suffers from an uncertain knowledge of the rates of the $^{17}O(p,\alpha)^{14}N$ and $^{17}O(p,\gamma)^{18}F$ reactions at stellar energies.

The reaction rate of interacting particles in a stellar environment with temperature T is given by the thermally averaged product of the cross section for the reaction and the relative speed of the particles

$$\langle \sigma v \rangle = K1(kT)^{-3/2} \int \sigma(E) E \exp(-E/kT) dE \quad (1)$$

with $\sigma(E)$ given by the Breit and Wigner formula in the case of a resonant reaction $A(a,b)B$

$$\sigma(E) = K2E^{-1}\Gamma_{\rm tot} S_r P_l(E)/P_l(E_r) \times [(E-E_r)^2 + \Gamma_{\rm tot}^2/4]^{-1} , \quad (2)$$

where the resonance strength S_r is given by

$$S_r = (2J_r+1)\Gamma_a \Gamma_b / \Gamma_{\rm tot} ; \quad (3)$$

J_r is the spin of the resonant level and $\Gamma_{a(b)}$ ($\Gamma_{\rm tot}$) the partial (total) widths for this level. $K1$ and $K2$ are constants depending on the masses of the nuclei. $P_l(E)$ is the penetrability function for the system $a + A$.

The $^{17}O(p,\alpha)^{14}N$ reaction cross section is expected to be dominated at stellar energies by a resonance at E_p(lab) = 70 keV, corresponding to the 5.673 MeV (1^-) level in ^{18}F. A subthreshold level at 5.605 MeV (1^-) could also play a significant role in the reaction rate both through the high-energy tail of the level and because of possible interference effects with the 5.673 MeV level. The other states which could be involved in the stellar reaction rates are the 5.603 MeV (1^+) level only bound by 3 keV against proton decay and possibly the 5.786 MeV (2^-) level for high-temperature processes.

The determination of the spectroscopic properties of all these levels (excitation energy, spin, isospin, and par-

tial and total widths) is of a critical significance for the evaluation of the fusion cross section at stellar energies. Recently, the excitation energy of the first level above the proton threshold in ^{18}F was determined[9] to be 5672.6 ± 0.3 keV, in disagreement with the previously measured value[10] of 5668 ± 2 keV. The change in the excitation energy of this level significantly affects the reaction rates for ^{17}O destruction during hydrogen burning in stars as reported in Ref. 11. From extensive studies through a variety of nuclear reactions,[1] spins, parities, and isospins of the aforementioned levels are now firmly established. The negative-parity levels are believed to be predominantly of 3p-1h structure with the most likely configuration $(d_{5/2}s_{1/2})^3p^{-1}$.[12]

While the radiative and alpha particle widths are known[1] for the levels at 5.605 and 5.673 MeV, only upper limits appear in the literature[13] for the proton widths. Since these levels are very close to the proton threshold, the total width is nearly equal to the alpha width. As a consequence, the resonance strength for the corresponding (p,α) reactions is essentially dependent on the value of the proton width, as immediately seen from Eq. (3). Level widths are connected to the corresponding reduced widths θ_p^2 through the relation

$$\Gamma_p = 2P_l\theta_p^2 \ .$$

The reduced widths θ_p^2 can be determined using direct transfer reactions through the measurement of spectroscopic factors. The value of spectroscopic factors determines the probability that the nuclear state produced in the direct reactions has its parentage based on the ground state of the target with the transferred particle in a shell-model state nlj. Thus, determination of Γ_p involves the calculation of single-particle widths which in turn requires the evaluation at a distance R of the radial part of the wave functions describing the target and transferred particle cluster. It is customary to scale θ_p^2 by the sum-rule limit and define dimensionless reduced widths θ_{pr}^2.

From a study of direct radiative capture of protons by ^{17}O, Rolfs and Rodney[13] give

$$\theta_{pr}^2(l=1) < 0.0003$$

for the 1^- level at 5.605 MeV,

$$\theta_{pr}^2(l=1) < 0.0001$$

for the 1^- level at 5.668 MeV (actually at 5.673 MeV), and

$$\theta_{pr}^2(l=2) < 0.002$$

for the 1^+ level at 5.603 MeV. A major conclusion from this experiment is that the $^{17}O(p,\alpha)^{14}N$ reaction has a considerably lower rate than previously assumed, and then the $^{17}O(p,\gamma)^{18}F$ channel cannot be neglected at stellar energies due to the contribution of the direct radiative capture in the cross section. Then, the CNO cycle would be tricycling.[13] However, in the experiment of Rolfs and Rodney,[13] the data analysis was carried out using the excitation energy of 5.668 MeV for the 1^- level. With the actual value of 5.6726 MeV, the gamma line observed in Ref. 13 can no longer be resolved from a contaminant line.[9] As a consequence, the upper limit given in Ref. 13 is no longer valid, which further points towards new measurements of the proton width for this level.

Since direct measurement of the $^{17}O+p$ reaction cross section at stellar energies is hardly feasible due to the low penetration of the Coulomb barrier, the present study was undertaken in order to reinvestigate the spectroscopic factors of levels close to the proton threshold using the $^{17}O(^3He,d)^{18}F$ reaction. The exact procedure followed in this work to relate spectroscopic factors to Γ_p is described in details in Secs. III and VI. In addition, the spectroscopic factors of most of the levels bound against proton decay in ^{18}F have been determined. From these measurements, some further information on the nuclear structure of ^{18}F has been obtained as compared to previous proton stripping studies.[14]

II. EXPERIMENTAL PROCEDURE

The experiment was run at the ORSAY MP Tandem, using a 15 MeV ^3He beam. The outgoing deuteron particles were detected with a position-sensitive proportional counter located at the focal plane of a split-pole spectrometer. Its length of fifty centimeters made it possible to investigate an excitation energy in ^{18}F ranging from about 0.3 to 6.5 MeV, with only one magnetic field exposure. The overall energy resolution has varied from 15 keV in a first run to 10 keV in a second one. The position sensitive counter was backed by a single-wire proportional counter and a plastic scintillator, ensuring a $(\Delta E - E)$ discrimination of various types of particles.

One of the main experimental difficulties of this work was that the targets had to be free of ^{18}O impurities which would have obscured the lines of astrophysical interest in ^{18}F. Since 100% enriched ^{17}O isotope is currently unavailable, we used a 20 keV energy beam of ^{17}O in the PARIS separator of the Centre de Spectrométrie Nucleaire et de Spectrometrie de Masse, (CSNSM) to implant the ^{17}O atoms onto self-supporting backings. The backings were made-up of 50 $\mu g/cm^2$ of Tantalum evaporated onto 20 $\mu g/cm^2$ carbon layers at the Orsay Institut de Physique (IPN) target service. They could barely support beam intensities of 2 μA from the separator. We finally succeeded in making two targets with 73 mC of ^{17}O ions implanted onto a 14 mm diameter surface.

Target thicknesses were measured by means of the $^{17}O(d,\alpha)$ reaction at the 2 MV Jussieu Ecole Normale Supérieure (ENS) Van de Graaff accelerator from comparison with a standard anodized ^{17}O target using techniques initiated by the Groupe de Physique des Solides (GPS) group at the Paris VII University.[15] Further Rutherford backscattering measurements with beams of 2 MeV α particles gave similar results. Finally, the ^{17}O content of our target was found to be $1.0\pm0.1\times10^{17}$ atoms/cm^2.

The angular distributions of the outgoing deuterons were measured at nine angles from 3° to 30° in the laboratory. The solid angle was 1.7 msr except for the measurement at 3° where the aperture was reduced to 0.5 msr due to the ^3He scattered flux. Exposures from 500 to 4400

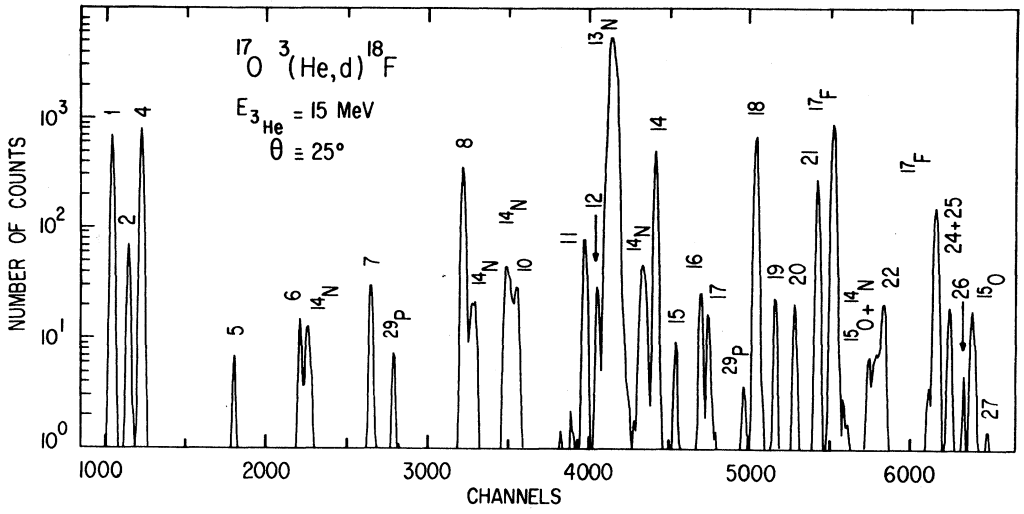

FIG. 1. Deuteron energy spectrum for the reaction $^{17}O(^3He,d)^{18}F$ at $\theta_{lab}=25°$ and $E_{inc}=15$ MeV. This spectrum was obtained with an exposure of 4343 μC. The numbers above the peaks refer to ^{18}F levels and are listed in Table II. Impurity groups arising from ^{12}C, ^{13}C, ^{14}N, ^{16}O, and ^{28}Si contaminants in the target are labelled by the appropriate residual nucleus.

μC were achieved for each angle. A solid-state detector was located at 135° within the reaction chamber for beam and target monitoring through the intensity of the elastically scattered ^{3}He particles. Data were registered event by event and analyzed off line. In this analysis, only events involving outgoing deuterons were selected and dead-time corrections were applied. Besides the levels of astrophysical interest, most of the known levels below the proton threshold[1] have been analyzed.

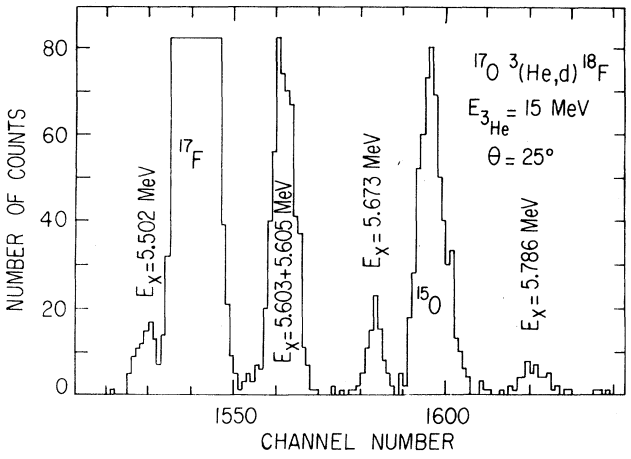

FIG. 2. A spectrum for the reaction $^{17}O(^3He,d)^{18}F$ collected at $\theta_{lab}=25°$ and corresponding to the levels close to the proton threshold. The final states are identified by their excitation energy in MeV. The contaminant line labelled ^{17}F (^{15}O) corresponds to the excitation of the level at 0.495 MeV (7.276 MeV) in ^{17}F (^{15}O) through the $^{16}O(^3He,d)^{17}F$ [$^{14}N(^3He,d)^{15}O$] reaction.

Absolute values of cross section were obtained from measurements of the target thickness and of the integrated beam currents. Independent of statistics, this procedure is estimated to give an accuracy of about 15% for the determination of the absolute cross sections.

A typical deuteron spectrum is shown in Fig. 1. An expanded view of the excitation energy region corresponding to the lines of astrophysical interest is displayed in Fig. 2. The two lines corresponding to the group of levels at 5.603+5.605 MeV and 5.673 MeV, respectively, are clearly apparent. It should be stressed that no pollution from the $^{18}O(^3He,d)^{15}N$ reaction appears in the experimental spectra, so that any contamination of the lines of interest by this reaction can be fully excluded.

III. DATA ANALYSIS AND DISTORTED-WAVE CALCULATIONS

The calculated angular distributions of deuterons were obtained using the distorted-wave Born approximation (DWBA) code DWUCK4.[16] For the levels bound against proton decay, the spectroscopic factors were extracted from the data using the relation

$$(d\sigma/d\Omega)_{exp}=N\sum_l C^2S(l)(d\sigma/d\Omega)^l_{DW} \times(2J_f+1)/(2J_i+1)(2j+1)\ ,$$

where C^2 is the isospin coupling coefficient and N is equal to 4.42 for (^{3}He,d) reactions. When necessary, a mixture of l values was fitted to the experimental points with a chi-square minimization computer program. The cross section for excitation of states above the proton threshold were calculated with the same code DWUCK4 according to the method of Vincent and Fortune.[17] Following this

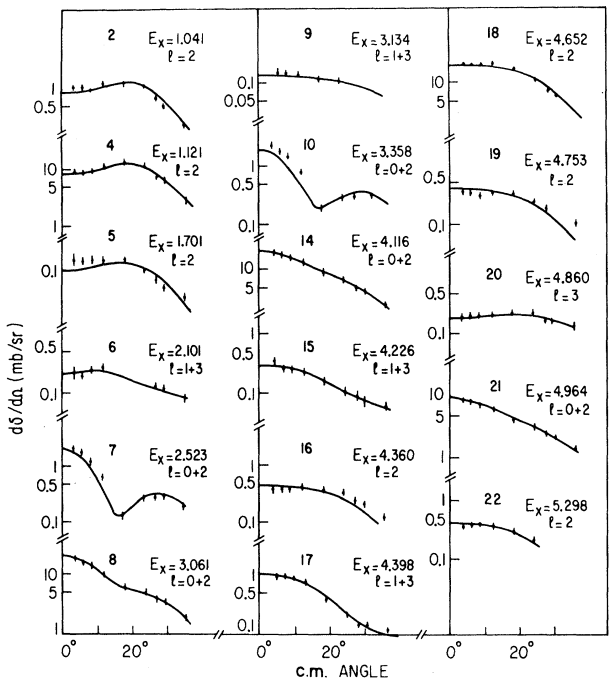

FIG. 3. Measured angular distributions from the $^{17}O(^3He,d)^{18}F$ reaction. Solid curves correspond to DWBA calculations with the indicated values of transferred partial waves. Final states are identified by their excitation energies in MeV and labelled by the same number as in Fig. 1. Vertical bars are statistical errors.

method, spectroscopic factors can be defined for unbound levels by

$$C^2S = \Gamma_p / \Gamma_{s.p.} ,$$

where $\Gamma_{s.p.}$ is a single-particle width calculated by taking a real optical potential of Woods-Saxon shape together with the Coulomb potential of the proton and target system. The strength of the real optical potential is adjusted so that the radial wave function at the energy of the resonance is asymptotically proportional to the irregular Coulomb wave function G/r. C^2S is given by the ratio of the observed differential cross section to the calculated DWBA single-particle differential cross section. The application of this procedure to the specific cases of the unbound levels at 5.673 and 5.786 MeV is developed in more details in Sec. VI.

The parameters used for the determination of the form factors are listed in Table I, together with the optical-potential parameters for the ^{3}He and deuteron channels.[18,19] They give a good agreement overall between the calculated and measured angular distributions of the outgoing deuterons as shown in Fig. 3. The spin-orbit term of the optical potential for the deuteron channel was taken equal to zero for mixed l calculations. Its influence is of less than a few percent at the involved angles.

IV. EXPERIMENTAL RESULTS

Angular distributions in the center-of-mass (c.m.) system of most of the levels in ^{18}F below an excitation energy of 5.8 MeV are shown in Fig. 3. The points are experimental data while the solid lines are angular distributions calculated as indicated earlier. The derived absolute spectroscopic factors for all the analyzed levels are given in Table II, together with the corresponding differential cross sections measured at 10° (lab angle). The cross section for excitation of the level at 1.081 MeV was found to be less than 15 μb/sr. The spectroscopic factors for the levels at 3.724, 3.791, 3.839, and 5.502 MeV could not be extracted due to pollution by ^{12}C and ^{16}O contaminants in the target. The DWBA analysis for the 5.603+5.605 MeV group will be discussed in Sec. VI since these levels are relevant to the astrophysical aspect of this work. A $d_{5/2}$ transfer was assumed for $l=2$ transitions to positive-parity levels with $T=0$ and odd spin. The obtained values for C^2S should be multiplied by a factor of 1.2 in the case of a $d_{3/2}$ transfer. For negative-parity levels, $1p$ transfer was assumed since hole states are known to take part in the wave function of the ground state of ^{17}O. Consideration of an alternative $2p$ transfer would decrease the spectroscopic factor by a factor of 2. The uncertainties in the values of the spectroscopic factors can be estimated to range from about 20% for the strongly excited states to about 50% for the weakly excited ones.

V. DISCUSSION OF THE NUCLEAR STRUCTURE ASPECTS

Nuclei in the region of the doubly magic nucleus ^{16}O are of considerable interest since they offer the possibility of studying the coexistence of both strongly deformed

TABLE I. Optical-model parameters used in the DWBA calculations. All potentials are of the Woods-Saxon form, with the usual notation (Ref. 18). The depth of the proton Woods-Saxon well V was adjusted so that the experimental binding energies (or resonance energies for unbound levels) are reproduced. The spin-orbit parameter λ is taken equal to 25 MeV.

Channel	V (MeV)	W (MeV)	W' (MeV)	$V_{s.o.}$ (MeV)	r_0 fm	a fm	r_c fm	r_w fm	a_w fm	$r_{s.o.}$ fm	$a_{s.o.}$ fm
$^3He+^{17}O$	156.0	6.0			1.05	0.829	1.4	2.4	0.592		
$d+^{18}F$	87.0	0.28	49.24	13.78	1.17	0.735	1.3	1.325	0.682	1.07	0.660
Bound state				$\lambda=25.0$	1.25	0.650	1.25				

TABLE II. Experimental information for the $^{17}O(^{3}He,d)^{18}F$ reaction. E_x and J^π values are taken from Refs. 1 and 9 for the level at 5.673 MeV.

E_x (MeV)	J^π	Level number	l	C^2S	$d\sigma/d\Omega$ (10°) mb/sr
0.937	3^+	1	0 2	(0.102) (0.306)[a]	6.9
1.041	0^+	2	2	0.96	1.15
1.121	5^+	4	2	0.89	11.2
1.701	1^+	5	2	0.035	0.16
2.101	2^-	6	1 3	0.01 0.04	0.27
2.523	2^+	7	0 2	0.014 0.011	0.63
3.061	2^+	8	0 2	0.21 0.62	9.7
3.134	1^-	9	1 3	0.007 0.039	0.13
3.358	3^+	10	0	0.014	0.78
4.116	3^+	14	0 2	0.17 0.68	13.4
4.226	2^-	15	1 3	0.012 0.018	0.23
4.360	1^+	16	2	0.074	0.43
4.398	4^-	17	1 3	0.022 0.015	0.75
4.652	4^+	18	2	1.04	21.3
4.753	0^+	19	2	0.18	0.34
4.860	1^-	20	3	0.078	0.22
4.964	2^+	21	0 2	0.17 0.51	6.5
5.297	4^+	22	2	0.02	0.36
5.603	1^+	24	2	0.12	0.72
5.673	1^-	26	1 3	0.006 0.014	0.08
5.786	2^-	27	1 3	<0.002 <0.004	0.04

[a]The $l=2$ admixture cannot be unambiguously determined because of resultant too smooth chi-square minima.

and spherical states in a mass region for which detailed calculations using shell-model wave functions can be handled. Deformed positive-parity states in ^{18}F may be constructed by breaking up the ^{16}O core in such a way as to promote two protons and two neutrons in the (sd) shell. These strong 4p-2h components, which can mix with the usual $2p$ components in the deformed states of ^{18}F, must be introduced to reproduce the correct number of levels and the large electric quadrupole transitions found in ^{18}F and ^{18}O (Ref. 20). Their existence is further supported by

TABLE III. Comparison of spectroscopic factors measured in this work and in Ref. 14.

E_x[a] (MeV)	$J^{\pi a}$	T^a	l	C^2S Present work	C^2S Ref. 14
1.041	0^+	1	2	0.96	0.96
1.121	5^+	0	2	0.89	0.83
3.061	2^+	1	0	0.21	0.13
			2	0.62	0.61
4.116	3^+	0	0	0.17	0.11
			2	0.68	0.62
4.652	4^+	1	2	1.04	0.81
4.964	2^+	1	0	0.17	0.22
			2	0.51	0.49

[a]See Ref. 1.

the strong excitation of some levels in ^{18}F by the $^{14}N(^{7}Li,t)^{18}F$ reaction.[21]

Proton stripping reactions excite states in the residual nucleus, which have parentage to the ground state of the target nucleus. The ^{17}O ground state is known to be predominantly $1d_{5/2}$ with a 3p-2h core-excitation component whose intensity ranges from a few percent up to 40% according to various calculations.[22,23] An experimental estimate of 4–6 % (Ref. 24) has been given for the amount of 3p-2h core-excitation configuration in ^{17}O ground state (g.s.), assuming a one-step process for the two-nucleon transfer reaction $^{17}O(^{3}He,p)^{19}F$ leading to the 3.910 MeV level in ^{19}F. If this estimate holds, the $^{17}O(^{3}He,d)^{18}F$ reaction should strongly excite the (sd) states while the intensity to the deformed positive-parity states with predominant 4p-2h components should only be a few percent. Hence the proton transfer reaction could give a quantitative estimate of the mixture of core-excited and usual $2p$ components in the deformed states of ^{18}F. Excitation of negative-parity levels involves proton transfer either to the very high-lying $2p_{3/2}$ orbit or to the $1p$ orbit through the 3p-2h component in ^{17}O (g.s.).

A. Positive-parity states

The absolute spectroscopic factors found for the most strongly excited levels in ^{18}F are compared in Table III with the previous results of Ref. 14. As mentioned earlier these states are of predominant $(d_{5/2}s_{1/2})$ configuration. Since there is good agreement between our work and that of Polsky *et al.*,[14] we agree with their conclusions about the configurations of these states.

The spectroscopic factors given in Table IV for the weakly excited states are of greater interest since they were not studied in the previous works.[14] For these states, the small values of the spectroscopic factors (a few percent) point toward the excitation of mixed (4p-2h+$2p$) configurations with small $2p$ amplitudes. This feature is illustrated more effectively in Table IV from a comparison of our results with calculated spectroscopic factors using the coexistence model of Refs. 20 and 25. In this model, deformed 4p-2h states are mixed with the usual $2p$ states. The deformed states are constructed either by coupling 1p-2h states to the $K=0$ ground-state band of ^{20}Ne used as a basis representation for the four nucleons in the (sd) shell[20] or by introducing three intrinsic core-deformed 4p-2h states classified according to their K quantum numbers.[25] A reasonable agreement is obtained between the experimental and calculated spectroscopic factors for the levels at 1.701 (1^+), 3.358 (3^+), 4.753 (0^+), and 5.603 MeV (1^+) (see Table IV). The largest disagreement is observed for the 2^+ state at 2.523 MeV and to a lesser extent for the 1^+ level at 4.360 MeV. For the latter level the DWBA fit to the experimental data is rather poor for angles larger than 20° (see Fig. 3).

TABLE V. Experimental spectroscopic factors for negative-parity levels bound against proton decay.

E_x[a] (MeV)	J^{π}[a]	T[a]	l	C^2S Present work
2.101	2^-	0	1	0.01
			3	0.04
3.134	1^-	0	1	0.007
			3	0.039
4.226	2^-	0	1	0.012
			3	0.018
4.398	4^-	0	1	0.022
			3	0.015
4.860	1^-	0	3	0.078

[a]See Ref. 1.

B. Negative-parity states

The spectroscopic factors derived for the negative-parity states below the proton threshold are given in Table V. According to previous studies of the structure of ^{18}F using gamma-ray spectroscopy techniques,[12] the negative-parity levels are expected to be predominantly 3p-1h states. The small values of spectroscopic factors found in this work is consistent with this picture having regard for the 4–6 % intensity of 3p-2h configurations found in ^{17}O (g.s.) in Ref. 24.

TABLE IV. Comparison of spectroscopic factors calculated in Refs. 20 and 25 with the experimental values obtained in the present work for weakly excited positive-parity states.

E_x[a] (MeV)	J^{π}[a]	T[a]	l	C^2S Present work	Calculated C^2S b	c
1.701	1^+	0	2	0.035	0.08	0.044
2.523	2^+	0	0	0.014	0.12	0.002
			2	0.011	0.053	0.000 15
3.358	3^+	0	0	0.014	0.012	0.016
4.360	1^+	0	2	0.074	0.163	0.19
4.753	0^+	1	2	0.18		0.25
5.297	4^+	0	2	0.12		
5.603	1^+	0	2	0.12	0.07	0.06

[a]See Ref. 1
[b]See Ref. 25.
[c]See Ref. 20.

VI. LEVELS OF ASTROPHYSICAL INTEREST

As indicated in the Introduction, four levels close to the $^{17}O+p$ threshold energy of 5.606 MeV could make significant contribution to the resonant part of the reaction rates for $^{17}O(p,\alpha)^{14}N$ and $^{17}O(p,\gamma)^{18}F$. These states have $E_x(J^\pi)=5.603$ MeV (1^+), 5.605 MeV (1^-), 5.673 MeV (1^-), and 5.786 MeV (2^-). The deuteron energy spectrum in the energy region close to the proton threshold is shown in Fig. 2 for a lab angle of 25°. From this figure, it is obvious that the lines corresponding to the states at 5.603+5.605, 5.673, and 5.786 MeV are clearly resolved.

A. The group of levels at 5.603 and 5.605 MeV

The angular distribution for the 5.603+5.605 group is shown in Fig. 4. The associated DWBA fit drawn in the same figure shows a typical $l=2$ transfer, which indicates a predominant population of the 5.603 MeV (1^+) level. The best fit obtained for a $l=1+3$ transfer is shown in the same figure (dashed line). The observed strong disagreement further indicates the weak excitation of the 5.605 MeV level. An upper limit of 35% (two standard deviations) has been estimated for the maximum contribution of the 5.605 MeV level, assuming a pure $l=1+3$ transfer for this state. This corresponds to spectroscopic factor values of

$$C^2S\ (l=1)<0.020$$

and

$$C^2S\ (l=3)<0.024\ .$$

Values of

$$C^2S\ (l=1)<0.0003$$

and

$$C^2S\ (l=3)<0.009$$

are given in Ref. 13. If the 5.605 MeV level is neglected in the analysis, a C^2S ($l=2$) of 0.12 is found for the 5.603 MeV state. A possible contribution of less than 35% for the 5.605 MeV level will not greatly affect this value which is in strong disagreement with the upper limit $C^2S<0.002$, obtained in Ref. 13, from a direct radiative capture experiment. As shown in Table II, the level at 5.603 MeV is fairly strongly populated in the $^{17}O(^3He,d)^{18}F$ reaction so that the single-step nature of the proton transfer is expected to hold well for this level. The evidence shown in Fig. 4 that the shape of the angular distribution for this state is very well reproduced by DWBA calculations reinforces the validity of the analysis based upon the single-step character of the transfer. Hence, a final value of 0.12±0.04 is given for this level. Agreement is reasonable between this value and the calculated one of 0.07 obtained from the coexistence model of Ref. 25.

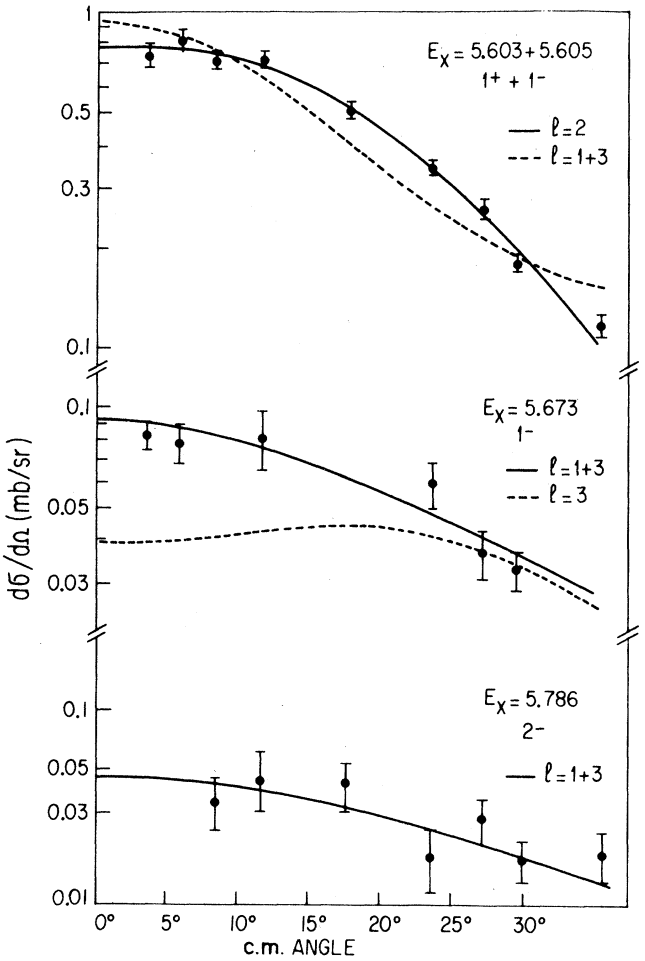

FIG. 4. Angular distributions from the $^{17}O(^3He,d)^{18}F$ reaction and associated DWBA fits for the levels at 5.603+5.605 MeV, 5.673 MeV, and 5.786 MeV. For the group of levels at 5603+5605 MeV, the dashed line is the best fit obtained for a $l=1+3$ transfer, corresponding to the excitation of the 1^- level. A DWBA fit corresponding to $l=3$ with $C^2S=0.015$ is also shown for the level at 5.673 MeV (dashed line).

B. The level at 5.673 MeV

In the experimental spectrum the 5.673 MeV line was obscured at laboratory angles of 7°, 10°, and 15° by a deuteron group leading to the 7.276 MeV level of ^{15}O excited by the reaction $^{14}N(^3He,d)^{15}O$. This contamination was due to a buildup of ^{14}N on the target during the experiment. For other angles, the resolution was good enough (especially in the second run) to easily resolve the line corresponding to the level at 5.673 MeV (see Fig. 2). For the measurement at 10°, the first one to be run and then the less polluted, the ^{14}N content was low enough to make feasible a subtraction of the contaminant contribution and then to get a value for the cross section of the reaction of interest. The derived angular distribution for the 5.673 MeV level is shown in Fig. 4 together with the DWBA fit. The cross section for excitation of this unbound state has been calculated using the DWBA code DWUCK4 according to the method of Vincent and Fortune[17] as explained in Sec. III.

This method is known to correctly deal with weakly unbound states,[26] provided the one-level Breit and Wigner formula is appropriate to the description of the corresponding resonance. This is likely to be the case for the 5.673 MeV level since interference effects with the 5.605 MeV level can hardly affect the position and the resonance width. As a further proof of the validity of this procedure, we checked that a smooth variation of cross section with changing threshold energy was observed for the 5.673 MeV level when crossing the proton binding energy. The calculation of Γ_p was achieved by solving Eq. 2.9 in Ref. 26 with the code DWUCK4. The obtained value of 1.2 10^{-11} MeV ($l=1$) does not change by more than 3% when the parameter r_0 (see Table I) is allowed to vary from 1.25 to 1.4 fm. This value was then combined with $C^2S=0.006$, derived from the analysis of the measured differential cross section, to give a final result of $\Gamma_p=7.1\ 10^{-14}$ MeV. In the analysis, a proton transfer to the $1p$ orbit, rather than to the $2p$ orbit, was assumed in view of the sizeable amount of 3p-2h configuration known to exist in ^{17}O (g.s.) and because of the high energy of the $2p_{3/2}$ orbit above the Fermi level. Anyway, the same final value is found for considering a transfer either to the $1p$ or to the $2p$ shell-model orbit. An amount of transfer to the $f_{7/2}$ orbit, corresponding to $C^2S=0.014$, was introduced in the analysis to obtain the best fit to the measured angular distributions of the deuterons leading to this level.

The rather low cross sections for population of the 5.673 MeV level result in a large uncertainty in the value of the spectroscopic factor. This uncertainty was estimated by varying the contributions due to the $l=1$ and $l=3$ transfers and looking at the resulting chi-square values. A value of

$$\Gamma_p=(7.1\pm4)\times10^{-14}\ \text{MeV}$$

is finally obtained including only statistical and instrumental errors. This value is in marked disagreement with the upper limit $\Gamma_p<1.3\ 10^{-15}$ MeV calculated from Ref. 13.

Further uncertainty in the value of Γ_p arises from the physical assumptions underlying the DWBA analysis of weakly populated levels. Probably the most serious difficulty comes from the assumption of the single-step character of the interaction. In order to estimate the maximum contribution of two-step processes to the excitation of the level at 5.673 MeV, coupled-channel calculations were performed using the code CHUCK2.[16] The two-step routes considered in the calculations are shown in Fig. 5. They involve inelastic scattering in the entrance and exit channels followed or preceded by $s_{1/2}$ or $d_{5/2}$ proton transfer. Inelastic scattering amplitudes were calculated with the deformation parameter $\beta_3=0.33$. The main component in the wave function of the 1^- state was described as resulting from the coupling of a proton and a neutron in orbits of the $2s_{1/2}$ and $1d_{5/2}$ shell with the 3^- vibrational state at 6.13 MeV in ^{16}O:

$$|1^-\rangle=a|3^-\rangle|d_{5/2}s_{1/2}\rangle_{T=0}+b|3^-\rangle|d^2_{5/2}\rangle_{T=0}$$
$$+c|3^-\rangle|d_{5/2}s_{1/2}\rangle_{T=1}+d|3^-\rangle|d^2_{5/2}\rangle_{T=1}$$

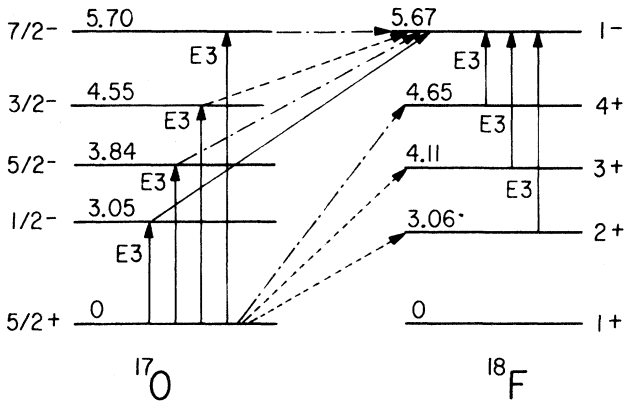

FIG. 5. Two-step routes considered in the CCBA calculations for the 5.673 MeV level. The solid (dashed) lines correspond to $l=0$ ($l=0+2$) transfers. The dot-dashed lines indicate $l=2$ transfers.

with

$$a^2+b^2=c^2+d^2=0.5$$

since the 1^- state is known to be an isospin mixed state[10] with approximately equal $T=0$ and $T=1$ components. To account for the single-step route, we added a fifth component

$$e|^{17}\text{O g.s.}\rangle|p_{3/2}{}^{-1}\rangle\ ,$$

where e is clearly very small. The additional term corresponding to the $f_{7/2}$ transfer was not included in the calculations. All the amplitudes corresponding to the various channels—including the single-step route—were added coherently, with a, b, c, d, and e adjusted to give the experimental value of the differential cross sections at 0° and 30°.

We observed that all solutions with $e=0$ lead to cross sections much higher at 30° than at 0°, in total disagreement with the experimental data. Furthermore, for the whole set of values of a, b, c, d, and e reproducing the experimental anisotropy $\sigma(0°)/\sigma(30°)$, e was always found larger than a value corresponding to a spectroscopic factor of 0.003 for the level at 5.673 MeV (0.006 for the DWBA analysis). Typical examples of the calculated differential cross sections are given in Fig. 6. It is worth noting that our calculations are expected to overestimate the effect of two-step processes because of our choice of maximum amplitude for proton transfer in the two-step routes and of pure octupole vibration excitation in the inelastic channels. Thus, the lowering of the spectroscopic factor by about a factor of 2 when taking into account two-step processes is likely to give a fair estimation of the uncertainty associated with the assumption of single-step transfer. The neglect of the $f_{7/2}$ transfer in the calculations is unlikely to modify significantly this conclusion.

Another assumption underlying the DWBA analysis is the negligible contribution of compound-nucleus processes to the cross section. We performed Hauser-Feshbach-type calculations to estimate the maximum contribution

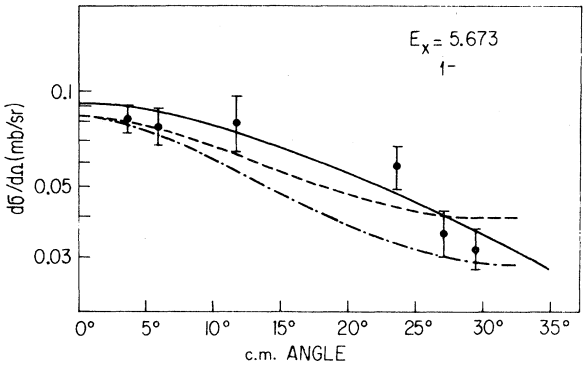

FIG. 6. Comparison between the calculated differential cross sections for the 5.673 MeV level, taking into account the two-step routes as explained in the text, and the experimental data. The solid line is the DWBA calculation. The dashed line is a CCBA calculation with $a=0.5$, $b=0.5$, $c=0.5$, $d=0.5$, and $e=0.055$. The dot-dashed line corresponds to the same calculations with $a=0.5$, $b=-0.5$, $c=0.5$, $d=0.5$, and $e=-0.055$.

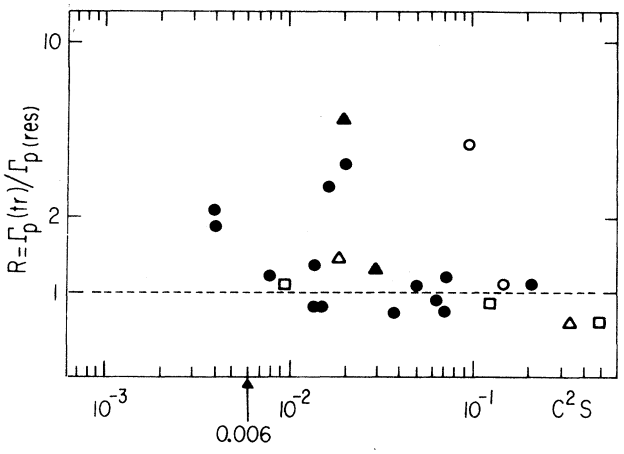

FIG. 7. Ratio of proton width values measured for the same levels from (^{3}He,d) reactions and resonant reactions, as a function of the spectroscopic factor extracted from the transfer reaction. The solid circles refer to the reaction ^{30}Si(^{3}He,d)^{31}P (Ref. 27), the open circles to the reaction ^{18}O(^{3}He,d)^{19}F, the open triangles to the reaction ^{13}C(^{3}He,d)^{14}N, the solid triangles to the reaction ^{16}O(^{3}He,d)^{17}F and the squares to the reaction ^{12}C(^{3}He,d)^{13}N. For all these reactions see Ref. 1 and references therein. The arrow indicates the value measured in the present work for the level at 5.673 MeV.

for such a process to the excitation of the 5.673 MeV state. The main difficulty in the calculation is the poor knowledge of level density for light nuclei. In order to overcome it, we performed our computations in a relative way. Hauser-Feshbach calculations were done for the 2^- neighboring state at 5.786 MeV, weakly populated, and we assumed that level to be purely excited through compound-nucleus decay. The results of the Hauser-Feshbach computation were normalized to the experimental cross sections for the 5.786 MeV level. The calculated ratio of cross sections for excitation of levels at 5.786 and 5.673 MeV was then used to give the maximum contribution of compound-nucleus mechanisms for the level at 5.673 MeV. We found a value of less than 0.02 mb/sr at 5°, to be compared with the experimental value of 0.08 mb/sr. The same method was also applied using the 1.081 MeV (0^-) level as a reference, instead of the 5.786 MeV one, and a similar upper value of 0.02 mb/sr was also calculated. Moreover, the angular distribution for compound-nucleus processes was found to be nearly isotropic for the 5.673 MeV level, in contrast with the experimental results (Fig. 4). The compound-nucleus contribution for the excitation of the 5.673 MeV level is thus negligible compared with the direct transfer component.

J. Vernotte *et al.*[27] have recently attempted to estimate the reliability of proton width values extracted from transfer reactions by comparing them to direct measurements using resonant reactions. Their data concerning the reaction ^{30}Si(^{3}He,d)^{31}P are shown in Fig. 7, together with other cases taken from literature and concerning various reactions with light nuclei. Namely, the ratio Γ_p (transfer)/Γ_p (resonant reactions) obtained for given levels are plotted as a function of the measured spectroscopic factor. For C^2S values larger than about 4×10^{-2}, the ratio is found very close to 1 in all cases but one. For smaller spectroscopic factors more scattering occurs in the data reflecting the increasing two-step and compound-nucleus effects. However, no deviation by more than a factor of 5 was found in all the analyzed data. It is clear that this value of 5, extracted from a statistical analysis, cannot be expected to give a definite answer to the question of the maximum uncertainty associated with the proton width measurements using (^{3}He,d) reactions. However, for the specific case of the level at 5.673 MeV, considering that the described two-step and compound-nucleus calculations only lower the DWBA value by a factor of 2, we retain the aforementioned factor of 5 as giving a conservative value for the lower limit of Γ_p and we finally adopt for the 1^- state at 5.673 MeV

$$\Gamma_p = 7.1^{+4}_{-5.7}10^{-14}\ \text{MeV}\ .$$

C. The level at 5.786 MeV

As shown in Fig. 2, the 5.786 MeV level is very poorly populated by the ^{17}O(^{3}He,d)^{14}N reaction. For so weakly excited levels two-step processes and/or compound-nucleus contributions can account for a large part of the cross section, and a very thorough analysis of these undirect processes is needed before any proton width value can be given. Unfortunately, a dominant compound-nucleus contribution cannot be ruled out for this level as was done for the 5.673 MeV state, since using the 1.081 MeV (0^-) level as a reference, values of about 0.02 mb/sr at 5° are calculated for the compound-nucleus process, similar to the excitation cross section of the level. Nevertheless, assuming a single-step transfer to the $1p$ orbit, a C^2S value of 0.002 is found from which a proton width of

$2.8\ 10^{-9}$ MeV can be deduced. The best fit to the angular distribution is obtained by adding a $1f$ component with $C^2S=0.004$. Since this level is of minor importance for the cold CNO cycle, no special effort was made to perform corresponding coupled-channel Born approximation (CCBA) calculations. Finally, only the upper limit $\Gamma_p < 2.8\ 10^{-9}$ MeV can be given as the result of the present work. A more restrictive value ($C^2S < 0.000\,6$) was given in Ref. 13.

VII. ASTROPHYSICAL IMPLICATIONS

A. Astrophysical S factors

The astrophysical cross section factors

$$S(E)=\sigma(E)E\exp(2\pi\eta)$$

were calculated for the reactions $^{17}O(p,\alpha)^{14}N$ and $^{17}O(p,\gamma)^{18}F$ (the quantity $2\pi\eta$ is the Sommerfeld parameter taken at the center-of-mass energy E of the reaction). The various widths and energies of the levels of astrophysical interest used in the calculations are presented in Table VI. For the 5.603 and the 5.673 MeV levels the radiative and alpha widths are taken from a recent work.[28] They are somewhat different from the values adopted in Ref. 13. The level at 5.605 MeV was not included in the calculations. Our upper limit for its proton width

$$[C^2S(l=1)<0.020]$$

leads to a contribution for this level of the same order of magnitude as the level at 5.603 MeV. However, with the upper limit given in Ref. 13

$$[C^2S(l=1)<0.000\,3]$$

the contribution of this level to any astrophysical calculation becomes vanishingly small.

The resulting S factors are displayed in Fig. 8. From this figure, it is clear that the contribution of the subthreshold level at 5.603 MeV to the astrophysical S factor cannot be neglected at low energy as previously believed.[13] However, the major change in the astrophysical S factor comes from our new value for the proton width of the 5.673 MeV level, now larger than the upper limit of Ref. 13 by a factor of 10–90. Actually, the astrophysical cross-section factors for the resonant reactions $^{17}O(p,\alpha)^{14}N$ and $^{17}O(p,\gamma)^{18}F$ are enhanced by the same factor, but now the alpha emitting reaction has an S factor considerably larger than the direct radiative capture one for nearly all proton energies lower than 150 keV (see Fig. 8). At higher energies, the 5.786 MeV state could affect the hydrogen burning of ^{17}O. Using the resonance parameters indicated in Table VI, the upper limit for the S factors at $E_p=0.180$ MeV for the reactions

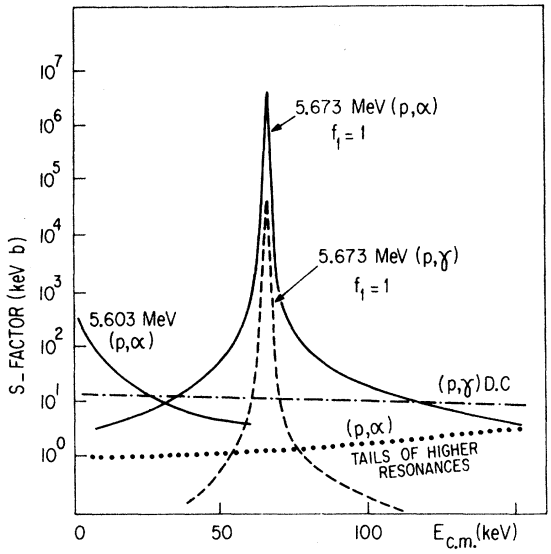

FIG. 8. Astrophysical S factors for the reactions $^{17}O(p,\alpha)^{14}N$ and $^{17}O(p,\gamma)^{18}F$ as a function of the center-of-mass energy of protons. The solid lines correspond to the $^{17}O(p,\alpha)^{14}N$ resonant reaction through the levels at 5.603 MeV (1^+) and 5.673 MeV (1^-). The tails of the higher resonances in the $^{17}O(p,\alpha)^{14}N$ reaction taken from Ref. 13 are indicated by dotted lines. The dashed lines correspond to the $^{17}O(p,\gamma)^{18}F$ reaction (5.673 MeV level) using resonance parameters of Table VI. The S factor corresponding to radiative capture through the 5.603 MeV level is negligible and not displayed in the figure. The dot-dashed line represents a calculation of the direct radiative capture taken from Ref. 13.

TABLE VI. Resonance parameters for the levels of astrophysical interest used in the reaction rate calculations. The Q value of the $^{17}O(p,\gamma)^{18}F$ is equal to 5.6062 (Ref. 1).

E_x (MeV±keV)	J^π	Γ_{tot} (eV)	Γ_α (eV)	Γ_γ (eV)	Γ_p (eV)
5.6034±0.27[a]	1^+	43.4±1.6	42.8±1.6[b]	0.485±0.046[b]	
5.6726±0.3[c]	1^-	131.4±5	130±5[b]	1.4±0.3[b]	$(7.1^{+4}_{-5.7})\times10^{-8}$
5.786±2.4[d]	2^-	0.044±0.030	0.022[e]	0.022[e]	$<2.8\times10^{-3}$

[a]Reference 10.
[b]Reference 28.
[c]Reference 9.
[d]Reference 1.
[e]Reference 12.

$^{17}O(p,\alpha)^{14}N$ and $^{17}O(p,\gamma)^{18}F$ is considerably larger than the contribution from both the direct radiative capture and the tails of the higher-lying resonances.

B. Reaction rates

Reaction rates introduced in stellar evolution codes are usually taken from the compilations of Fowler *et al.*[29,11] In Ref. 29 resonant reaction rates are expressed as a function of the stellar temperature

$$N_A\langle\sigma v\rangle = C_8 T_9^{-3/2}\exp(-C_9/T_9) ,$$

where C_8 and C_9 are two coefficients depending, respectively, on the strength and the energy of the resonance and where the temperature T is given in units of $T_9 = T/10^9$ K. N_A is Avogadro's number. This expression results from an approximate solution of Eq. (1).

For the specific case of the resonance corresponding to the level at 5.673 MeV, the coefficients C_8 and C_9 of Ref. 11 for the $^{17}O(p,\alpha)^{14}N$ reaction were calculated using the measurements of Rolfs and Rodney.[13] For the 5.786 MeV level, the origin of the values of the coefficients C_8 and C_9 in Ref. 11 is somewhat more obscure. We calculated the new values of these coefficients using the present results for proton widths and updated values of the 1^- state excitation energy[9] and of the other parameters of the resonances (see Table VI). We find for the resonant part of the reactions $^{17}O(p,\alpha)^{14}N$

$$N_A\langle\sigma v\rangle = f_1[2.94\times10^{-3}T_9^{-3/2}\exp(-0.767/T_9)] + f_2[98T_9^{-3/2}\exp(-2.077/T_9)] .$$

The first term corresponds to the resonance at $E_p = 0.066$ MeV and the second one to that at $E_p = 0.180$ MeV. f_1 and f_2 are confidence coefficients introduced to take into account the uncertainties in the measurements. From the preceding discussion f_1 ranges from 1.5 to 0.2 and f_2 ranges from 0 to 1 since we only measured an upper limit for the strength of the resonance at $E_p = 0.180$ MeV (c.m.).

The small contribution due to the low-energy tail of the resonance at 0.066 MeV must also be revised, giving

$$f_1\{2.8\ 10^{11}T_9\exp[-16.667/T_9^{1/3}-(T_9/0.040)^2]\} .$$

An additional contribution to the reaction rate due to the subthreshold state at 5.603 MeV has been calculated according to the following analytical expression:

$$N_A\langle\sigma v\rangle = 1.78\times10^5 T_9^{-2/3}\exp(-16.669T_9^{-1/3})/(0.479T_9^{2/3}+0.003\,12)^2 ,$$

the coefficients being fitted to reproduce the exact numerical integration of Eq. (1) within an uncertainty of a few percent.

The other terms given in Ref. 11 are unchanged. They are of minor importance except for very low temperatures. The effect of the level at 5.605 MeV has been neglected. This could induce some minor underestimation of the reaction rates at very low temperatures ($T_9 < 0.015$), only in case the actual proton width value is close to our conservative upper limit.

The same comments apply for the rate of the reaction $^{17}O(p,\gamma)^{18}F$, with

$$N_A\langle\sigma v\rangle = f_1[3.2\ 10^{-5}T_9^{-3/2}\exp(-0.767/T_9)] + f_2[98.0T_9^{-3/2}\exp(-2.077/T_9)] .$$

The other terms in the expression of Ref. 11 are unchanged.

These expressions are given to be easily introduced in nucleosynthesis codes. However, in the forthcoming calculations Eq. (1) has been exactly solved, including the dependence of the partial widths on E. The main interest of a full calculation is to make it possible to treat the slowly varying tails of the resonances on the same foot as the region near the maximum of the Breit and Wigner shape.

The ratio of the rate of the $^{17}O(p,\alpha)^{14}N$ reaction to the $^{17}O(p,\gamma)^{18}F$ one is displayed in Fig. 9 as a function of stellar temperature, using our values of the reaction rates. For all temperatures ranging from $T_9 = 0.01$ to $T_9 = 0.1$, the $^{17}O(p,\alpha)^{14}N$ rate largely exceeds the $^{17}O(p,\gamma)^{18}F$ rate.

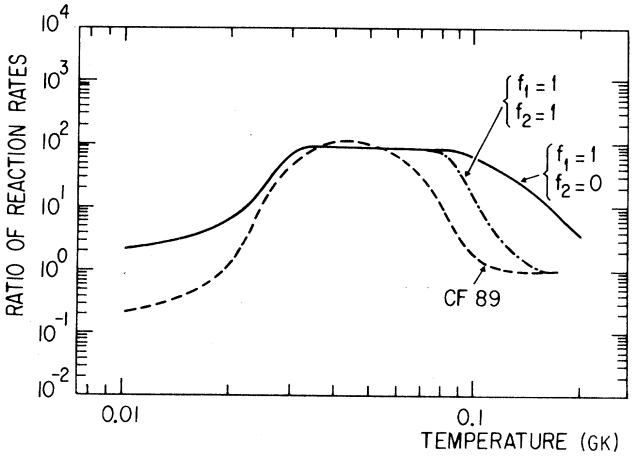

FIG. 9. Ratio of the reaction rate for $^{17}O(p,\alpha)^{14}N$ to that for $^{17}O(p,\gamma)^{18}F$ as a function of stellar temperature. In the reaction rates are included the effects of the subthreshold state at 5.603 MeV and of the level at 5.673 MeV with $f_1 = 1$. The curves labeled $f_2 = 0$ and $f_2 = 1$ correspond to the values $\Gamma_p = 0$ and $\Gamma_p = 2.8\ 10^{-9}$ MeV for the level at 5.786 MeV (see text). The reaction rate for $^{17}O(p,\gamma)^{18}F$ includes the effect of the direct radiative capture as given in Ref. 13. The dashed curve corresponds to the ratio obtained using the reaction rates of Ref. 11, with $f_1 = f_2 = 1$.

In the range of temperatures for which the 5.786 MeV level may significantly contribute to the rates, i.e., $T_9 > 0.1$, the $^{17}O(p,\alpha)^{14}N$ reaction is again largely dominant, except for $T_9 > 0.2$ if the actual proton width of the level at 5.786 MeV is close to its maximum value ($f_2 = 1$). Therefore, with the revised values of the proton reduced widths of the threshold levels, the sequence of reactions $^{17}O(p,\gamma)^{18}F(\beta^+,\nu)^{18}O(p,\alpha)^{15}N$ is of less importance than previously thought.[13]

C. Isotopic abundance ratios

In stars where the CNO cycle operates at low temperatures the NO cycle does not necessarily reach equilibrium, due to the low cross sections of certain reactions such as $^{16}O(p,\gamma)^{17}F$. In that case, the time evolution of the nucleosynthetic processes must be taken into account. Predictions for oxygen isotopic abundances using the Brussels-Saclay stellar model code[30] will be studied further in a separate paper. In the present discussion, we assume that the CNO cycle operates at equilibrium. Such calculations can at least give a qualitative insight into some of the involved physical processes.

The relative abundance of the elements ^{17}O and ^{16}O in stars undergoing the CNO process approaches an equilibrium value given by

$$^{16}O/^{17}O = \langle \sigma v \rangle_{17} / \langle \sigma v \rangle_{16} ,$$

where $\langle \sigma v \rangle_{16}$ is the rate of the reaction $^{16}O(p,\gamma)^{17}F$, and $\langle \sigma v \rangle_{17}$ is the sum of the rates of the $^{17}O(p,\alpha)^{14}N$ and $^{17}O(p,\gamma)^{18}F$ reactions. The $^{16}O/^{17}O$ equilibrium abundance ratios are calculated as a function of temperature taking into account the three levels at 5.603, 5.673, and 5.786 MeV in ^{18}F. For $^{16}O(p,\gamma)^{17}F$, the reaction rate was extracted from the compilation of Fowler *et al.*[11] The results are plotted in Fig. 10 together with the $^{16}O/^{17}O$ ratios observed in the atmosphere of seven red giants assumed to be ascending the giant branch for the first time.[3] The dispersion in the observations is illustrated by the two horizontal lines corresponding to the extreme measured values. The calculations were performed for the set of values $f_1 = 1$, $f_2 = 0$, and $f_1 = 0.2$ (see Sec. VII B), and $f_2 = 0$. The possible effect of the level at 5.786 MeV is illustrated by the calculations corresponding to $f_1 = 1$, $f_2 = 1$. While, with the reaction rates of Ref. 11, $^{16}O/^{17}O$ is lower than the observed values at all temperatures, the reaction rates of Sec. VII B lead to $^{16}O/^{17}O$ larger than the observation for temperatures higher than about $T_9 = 0.030$. For the considered red giant stars the convective envelope (where $^{16}O/^{17}O$ should be nearly equal to the solar value of 2485) is expected to be mixed down to a point where the nuclear material is enriched in ^{17}O because of the CNO process. Thus, using the reaction rates of this work, the observations of $^{16}O/^{17}O$ given in Ref. 3 can probably be reproduced only by introducing more severe mass losses than usually assumed in standard evolutionary models. Actually, only the insert of the new reaction rates into sophisticated stellar evolution codes could make it possible to clearly investigate how the observed surface abundances are related to the physical processes in the star.

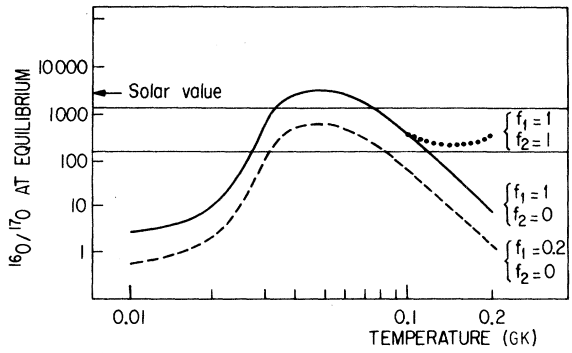

FIG. 10. $^{16}O/^{17}O$ isotopic abundance ratio assuming that the CNO cycle operates at equilibrium. The solid line is the result of a calculation using the reaction rates measured in this work with $f_1 = 1$ and $f_2 = 0$ as explained in the text. The dashed line corresponds to $f_1 = 0.2$ and $f_2 = 0$. The $^{16}O/^{17}O$ values obtained with $f_2 = 1$ and $f_1 = 1$ are also shown as a dotted line. The possible influence of the level at 5.786 MeV is effective only for $T9 > 0.1$. The ratios observed in seven red giant stars (Ref. 3) range from 1100 to 160. The extreme value are indicated by the solid horizontal lines, and the solar value by the arrow.

The recent observation[5,7] of $^{16}O/^{17}O$ ratios in *MS*-, *S*-, and *N*-type carbon stars has revealed much larger $^{16}O/^{17}O$ ratios than expected. These large ratios, close to the interstellar medium ones are extremely difficult to explain[7] in terms of present theories of the evolution of stars in the asymptotic giant branch, even when using the highest permitted value of the reaction rates of Ref. 11. For such evolved stars, the observed $^{16}O/^{17}O$ ratios should be easier to understand using the present value of the reaction rates, whose effect is to increase the destruction rate of ^{17}O.

VIII. SUMMARY

In this study, we have measured the spectroscopic factors of most of the levels in ^{18}F up to $E_x = 5.786$ MeV, using the $^{17}O(^3He,d)^{18}F$ reaction at a bombarding energy of 15 MeV. For the levels bound against proton decay, some evidence is found of the excitation of states with 4p-2h deformed configurations. The main purpose of this study was to reinvestigate the proton widths of the levels near the proton threshold, that information being needed to calculate the relevant reaction rates in the stellar energy region. The rate for the $^{17}O(p,\alpha)^{14}N$ reaction destroying ^{17}O in stars where the CNO cycle operates was found to be up to a factor of 10–90 larger than the previous

values. These new reaction rates probably imply severe mass losses in order to reproduce the observed overabundance of ^{17}O in stars on the first ascent to the giant branch. In contrast, the low ^{17}O abundance in stars on the giant asymptotic branch could find a more straightforward explanation within the framework of the available theoretical codes.

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