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Broad levels in ^{17}O and their relevance for the astrophysical *s* process

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Levels in ^{17}O affect the astrophysical *s* process in two opposite ways. The neutron production is enhanced by resonances in the ^{13}C$(\alpha,n)^{16}$O reaction at excitation energies around 7 MeV in ^{17}O, and the number of available neutrons is reduced by low-lying resonances in the ^{16}O$(n,\gamma)^{17}$O reaction corresponding to levels in ^{17}O with excitation energies of 4–5 MeV. The present work uses the ^{19}F$(d,\alpha)^{17}$O reaction to determine absolute widths of the relevant levels in ^{17}O. The results improve the uncertainties of the previously adopted values and resolve a discrepancy between recent studies for the $1/2^+$ level close to the threshold of the ^{13}C$(\alpha,n)^{16}$O reaction. In addition, improved excitation energies and widths are provided for several states in ^{17}O up to excitation energies close to 8 MeV.

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Introduction. It is well known that about one-half of the nuclei heavier than iron are synthesized in the astrophysical slow neutron capture process (*s* process). The main component of the *s* process is assigned to thermally pulsing AGB stars where neutrons are generated by the ^{13}C$(\alpha,n)^{16}$O reaction at low temperatures ($kT \approx 8$ keV) in the long interpulse phases and by the ^{22}Ne$(\alpha,n)^{25}$Mg reaction at higher temperatures ($kT \approx 23$ keV) in the shorter pulses. The weak component of the *s* process occurs in more massive stars with temperatures up to about $kT \approx 90$ keV [1–4]. The role of levels in ^{17}O for the *s* process is twofold. First, levels close to and above the ^{13}C-α threshold enhance the resonant neutron production in the ^{13}C$(\alpha,n)^{16}$O reaction. Second, the number of neutrons available for capture reactions on heavy nuclei is reduced by resonances in the ^{16}O$(n,\gamma)^{17}$O reaction which correspond to levels in ^{17}O close above the ^{16}O-n threshold. Thus, the nucleus ^{16}O may act as a neutron poison via the ^{16}O$(n,\gamma)^{17}$O reaction. A detailed study of the role of ^{16}O as neutron poison for the *s* process will be given elsewhere [5].

The present study attempts to provide improved level properties of states in ^{17}O. Although many experiments have been done over the last decades, the adopted values for excitation energies E^* and total widths Γ are often adopted in Ref. [6] from early neutron scattering data [7,8]. These data affect the stellar reaction rates of the ^{13}C$(\alpha,n)^{16}$O and ^{16}O$(n,\gamma)^{17}$O reactions. In addition, the knowledge of these level properties is essential for the analysis of indirect experimental data for the ^{13}C$(\alpha,n)^{16}$O reaction rate. The ^{19}F$(d,\alpha)^{17}$O reaction has been chosen for the present study because practically all levels in ^{17}O are populated with sufficient statistics.

In this Rapid Communication the experimental procedure is briefly described, and the measured excitation energies E^* and total widths are listed. We then focus on the main motivation of the present study which is the analysis of the $1/2^+$ state very close to the ^{13}C-α threshold. We present the results for the two lowest resonances in the ^{16}O$(n,\gamma)^{17}$O reaction ($3/2^-$, $E^* = 4.554$ MeV and $3/2^+$, $E^* = 5.085$ MeV). Some interesting details for other levels will be discussed.

Experimental procedure and results. A first try to populate states in ^{17}O with the ^{16}O(d,p) reaction had shown to produce too much background from the other components of the SiO_2 or Al_2O_3 targets. The present work used the ^{19}F$(d,\alpha)^{17}$O reaction to determine total widths of levels in the residual ^{17}O nucleus. The pickup of a proton and a neutron is supposed to populate rather unspecifically all levels in the final nucleus. The experiment has been performed at the MLL tandem accelerator of the Munich universities where a high-resolution Q3D magnetic spectrograph is available. A deuteron beam was accelerated to an energy of 22 MeV and focused onto the target with an average intensity of more than 0.6 μA. As target we used ^{6}LiF with a thickness of 46 μg/cm^2 evaporated onto a 12 μg/cm^2 carbon foil. The ^{6}Li has the advantage that the (d,α) reaction leads to another α particle with no excited states. The outgoing α particles were momentum analyzed with the Q3D spectrograph [9]. The identification and position measurement was performed with the 0.89 m long focal plane detector [10]. It consists of a proportional counter for energy loss and position measurement and a scintillator measuring the residual energy. α spectra were taken with two settings: at a scattering angle of 15° and an excitation energy range between 3750 keV and 6200 keV and a long run at 10° and between 5500 and 7800 keV. Since the position along the focal plane is not a linear function of the particle energy we have used lines in ^{17}O for an internal calibration with a quadratic polynomial. And, since the slope of the calibration is not constant, the channel contents were accordingly transformed as well as their uncertainties.

The calibrated spectra are shown in Figs. 1 and 2. All lines were fitted using a Gaussian or, for broad peaks, a Lorentzian line shape. The energy resolution of 20 keV (FWHM) is mainly caused by the difference in energy loss of the 22 MeV

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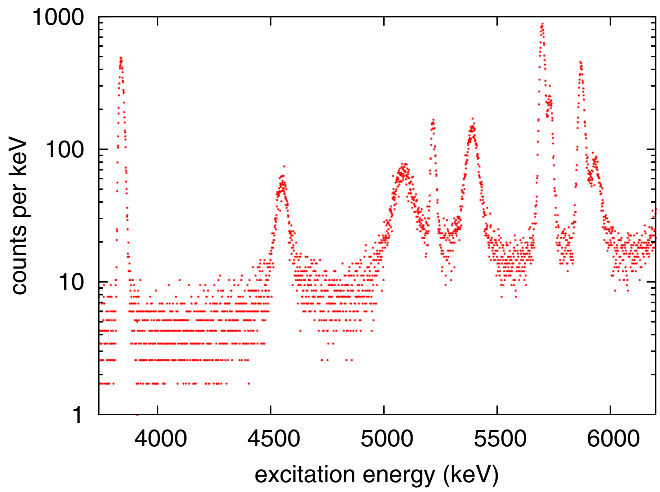

FIG. 1. (Color online) Low energy spectrum for the ^{19}F$(d,\alpha)^{17}$O reaction at $\Theta_{\text{lab}} = 15^\circ$.

deuterons and the 24.9 MeV (for $E^* = 6.36$ MeV) α particles. To fit the broad resonance at 6.36 MeV we used a large range of the spectrum from about 5.5 MeV to 7.5 MeV, excluding narrow peaks but including the broad peak at 7.20 MeV which extends down to the high energy tail of the 6.36 MeV line. For the background a cubic polynomial was used. Besides fitting with a constant width, the width of the 6.36 MeV line was also taken proportional to the velocity of the neutron, to be emitted, via the energy above the neutron-threshold at $E_{\text{thr}} = 4.143$ MeV as

$$\Gamma = \Gamma_0 \times [1 + 1/2(E - E_0)/(E_0 - E_{\text{thr}})], \qquad (1)$$

with Γ_0 the width at the resonance energy E_0. That improved the χ^2 by about 1%, reduced the resonance energy by 0.8 keV,

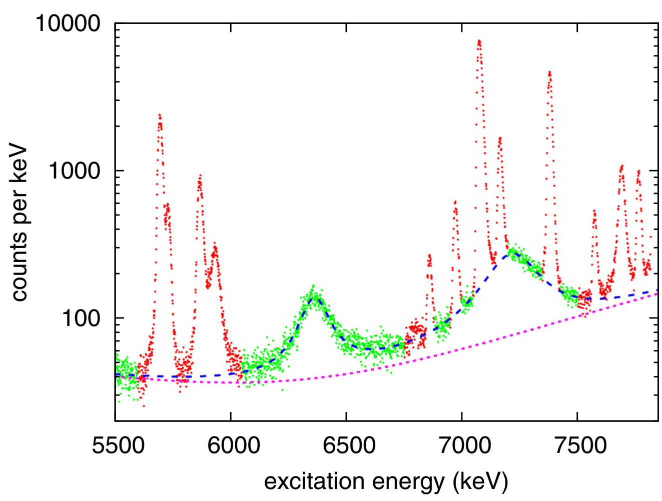

FIG. 2. (Color online) High energy spectrum for the ^{19}F$(d,\alpha)^{17}$O reaction at $\Theta_{\text{lab}} = 10^\circ$. The data ranges that have been used to fit the two Lorentzians are indicated by the green (lighter) dots. The simultaneously fitted background (dotted) and the total fit function (dashed) are also shown. The strongest peak at 7075 keV is the only background line from the ^{16}O$(d,\alpha_0)^{14}$N reaction.

but did not affect the width. The best fit has a $\chi^2/\text{dof} = 1344/1228$. The resonance curve in fact is a Voigt-profile which is the convolution of a Gaussian and a Lorentzian and does not have an analytical solution. Therefore we have used the parametrization of Olivero and Longbothum [11]

$$f_V \approx 0.5346 \times f_L + \sqrt{0.2166 \times f_L^2 + f_G^2} \qquad (2)$$

to extract the Lorentzian width $f_L = \Gamma$ from the Voigt width f_V (fitted) and the experimental Gaussian width $f_G \approx 20$ keV (FWHM). The results for the 6.36 MeV resonance as well as for all other states in ^{17}O between 3.8 MeV and 7.8 MeV are given in Table I. To accommodate the uncertainty of the intrinsic energy calibration an uncertainty of 0.3 keV has been added in quadrature to the uncertainties of the fitted excitation energies.

The $1/2^+$ *threshold level at* $E^* = 6.36$ *MeV*. We first focus on the neutron production in the s process. The ^{13}C$(\alpha,n)^{16}$O reaction operates at very low temperatures of $kT \approx 8$ keV; the Gamow window for this temperature is located at $E \approx 190$ keV; with the α separation energy $S_\alpha = 6358.69$ keV [12] this corresponds to an excitation energy of $E^* \approx 6550$ keV. (Note that all energies E are given in the center-of-mass system except explicitly noted; excitation energies in ^{17}O are denoted by E^*.) A detailed R-matrix study has taken into account 84 levels in ^{17}O from $E^* = 0$ to $E^* \approx 20$ MeV to derive the astrophysical S factor $S(E)$ and the reaction rate $N_A\langle\sigma v\rangle$ of the ^{13}C$(\alpha,n)^{16}$O reaction [13]. However, the careful inspection of the level scheme of ^{17}O shows that the astrophysical S factor in the Gamow window is strongly affected by the properties of one particular broad $1/2^+$ state close to the α threshold. The adopted parameters of this $1/2^+$ state have been derived mainly from neutron scattering: $E^* = 6356 \pm 8$ keV, $E = -3$ keV, $\Gamma = 124 \pm 12$ keV [6–8]. This level will be called "threshold level" (TL) in the following.

The TL leads to a resonant (Breit-Wigner) contribution to the cross section

$$\sigma(E) = \frac{\pi}{k^2}\,\frac{\Gamma_\alpha(E)\,\Gamma_n(E+Q)}{(E - E_R)^2 + \Gamma^2/4} \qquad (3)$$

with the wave number k and the energy-dependent widths Γ_α and Γ_n for the α and the neutron channel. The total width is practically identical to the neutron width: $\Gamma \approx \Gamma_n$. The spin factor $\omega = \frac{2J_R+1}{(2J_P+1)(2J_T+1)} = 1$ for this $1/2^+$ state has been omitted in Eq. (3). Obviously, the cross section scales linearly with $\Gamma_\alpha(E)$. In the Gamow window we have $E - E_R > \Gamma/2$, and thus the cross section is also roughly proportional to $\Gamma_n(E+Q)$.

Because an adopted neutron width Γ_n is available [6], most recent work has focused on α-transfer experiments and the indirect determination of $\Gamma_\alpha(E)$ of the TL using spectroscopic factors, reduced widths, or asymptotic normalization coefficients [14–19]. These studies have been complemented by a Trojan horse experiment [20,21]. A direct determination of Γ_α is impossible for a subthreshold state and practically not possible for a state very close above the threshold. Direct experimental data for the ^{13}C$(\alpha,n)^{16}$O reaction reach energies down to about 270 keV [22]. Further experimental data can be

TABLE I. Excitation energies E^* and Lorentzian widths Γ for states in ^{17}O from this work compared to the adopted values [6]. We have fitted Lorentzians (L) or Gaussians (G, *width printed in italics*) respectively to the lines with widths FWHM, and deduced the intrinsic width Γ for the Lorentzians as described in the text.

J^π	E^* (keV) [6]	Γ (keV) [6]	fit function	E^* (keV)[a]	FWHM (keV)	Γ (keV)[a]
$5/2^-$	3842.76 ± 0.42	$\tau \leqslant 25$ fs	G[b]	3842.9 ± 0.4	*21.52 ± 0.21*	
$3/2^-$	4553.8 ± 1.6	40 ± 5	L[b]	4551.4 ± 0.7	48.2 ± 1.7	38.1 ± 2.8
$3/2^+$	5084.8 ± 0.9	96 ± 5	L	5087.7 ± 1.0	93.4 ± 2.6	88 ± 3
$9/2^-$	5215.77 ± 0.45	<0.1	G[b]	5216.5 ± 0.4	*21.6 ± 0.5*	
$3/2^-$	5379.2 ± 1.4	28 ± 7	L	5388.8 ± 0.6	49.4 ± 1.1	39.0 ± 2.1
$7/2^-$	5697.26 ± 0.33	3.4 ± 0.3	G[b]	5697.5 ± 0.5	*21.97 ± 0.14*	
$(5/2^-)$	5732.79 ± 0.52	<1	G[b]	5731.6 ± 0.4	*21.97 ± 0.14*	
$3/2^+$	5869.07 ± 0.55	6.6 ± 0.7	G[b]	5869.7 ± 0.6	*25.2 ± 0.7*	
$1/2^-$	5939 ± 4	32 ± 3	L	5931.0 ± 1.1	44.7 ± 3.0	33 ± 5
$1/2^+$	6356 ± 8	124 ± 12	L	6363.4 ± 3.1	139 ± 4	136 ± 5
$(5/2^+)$	6862 ± 2	<1	G[b]	6860.7 ± 0.4	*18.8 ± 0.7*	
$(7/2^-)$	6972 ± 2	<1	G[b]	6972.6 ± 0.4	*18.8 ± 0.4*	
$5/2^-$	7165.7 ± 0.8	1.38 ± 0.05	G[b]	7165.4 ± 1.8	*20.0 ± 0.5*	
$3/2^+$	7202 ± 10	280 ± 30	L	7216 ± 4	264 ± 7	262 ± 7
$5/2^+$	7379.2 ± 1.0	0.64 ± 0.23	G	7380.1 ± 0.4[c]	*19.8 ± 0.5*	
$5/2^-$	7382.2 ± 1.0	0.96 ± 0.20	G	7380.1 ± 0.4[c]	*19.8 ± 0.5*	
$3/2^-$	7559 ± 20	500 ± 50				
$(7/2^+)$	7576 ± 2	<0.1	G[b]	7573.5 ± 0.6	*18.4 ± 1.2*	
$7/2^-$	7688.2 ± 0.9	14.4 ± 0.3	L[b]	7689.2 ± 0.6	25.1 ± 1.3	12 ± 4
$11/2^-$	7757 ± 9	–	G[b]	7763.6 ± 0.4	*18.1 ± 0.7*	<4

[a]This work.
[b]Used for energy calibration.
[c]Not resolved.

found in Refs. [13,23,24]; earlier experiments are summarized in the NACRE compilations [25,26].

The present experiment improves the excitation energy E^* and the total width Γ of the TL. Besides the direct impact on the cross section in Eq. (3) and the resulting reaction rate, improved E^* and Γ may also affect the analysis of the transfer experiments [14–18]. In all these studies the adopted values for E^* and Γ of the TL [6] had to be used to fit small and broad peaks in spectra with significant background. Contrary to the transfer experiments [14–19], the recent Trojan horse experiment [20,21] has attempted to derive Γ and Γ_α simultaneously; but also the Trojan horse experiment had to use the adopted excitation energy E^*. Huge discrepancies of about a factor of 30 for Γ_α and the contribution of the TL to the ^{13}C(α,n) ^{16}O reaction rate have been derived from the transfer data and the Trojan horse experiment [14–21]. This may at least partly be attributed to the use of the adopted values E^* and Γ which are revised in the present study. Following the discussion in Ref. [19], it has to be noted for completeness that the very low result of [16] should be excluded.

Unfortunately, recent studies provide also discrepant results for the total width Γ in contradiction to the adopted values. The R-matrix fit by Heil *et al.* [13] quotes $E^* = 6379.5$ keV and $\Gamma = 158.1$ keV, i.e., both values are larger and show an about 3σ deviation from the adopted values. Contrary to the large values in the R-matrix study [13], the recent Trojan horse experiment claims a smaller width of $\Gamma = 107 \pm 5_{\rm stat}{}^{+9}_{-5}{}_{\rm norm}$ keV [20]. A first analysis of these data has found an even smaller value of $\Gamma = 83^{+9}_{-12}$ keV [21].

The present results for this TL are $E^* = 6363.4 \pm 3.1$ keV and $\Gamma = 136 \pm 5$ keV. The new excitation energy E^* is 7.4 keV higher than the adopted value. The uncertainty of E^* has been reduced by more than a factor of two. The new result for E^* remains within 1σ of the adopted value. The higher excitation energy changes this level from a subthreshold level to a resonance at $E = 4.7 \pm 3$ keV. The new width of $\Gamma = 136 \pm 5$ keV is 12 keV higher than the adopted width, and it is close to the average value of the high R-matrix result [13] and the low Trojan-horse result [20]. The uncertainty of the width has been improved significantly.

At first view it seems to be a simple task to estimate the impact of the present new results on the ^{13}C(α,n) ^{16}O cross section and reaction rate using Eq. (3). The following estimates are given for a typical s process temperature of $kT \approx 8$ keV which corresponds to a most effective energy $E \approx 190$ keV. Keeping Γ_α, the cross section is enhanced by about 7% from the increased new energy E^* of the TL, and the larger new total width Γ leads to an increase of the cross section by about 8%. Combining both new values for E^* and Γ increases the cross section by 15%. However, this direct impact of the new values has to be complemented by an indirect impact which is difficult to quantify. As pointed out above, the experimental determination of $\Gamma_\alpha(E)$ of the TL by indirect methods often requires a peak fitting for the TL. In most cases these fits had to use the adopted values for E^* and Γ because the corresponding peaks were very broad (and sometimes located on non-negligible background). Thus, the present new results for E^* and Γ of the TL should be used in a reanalysis of the previous transfer and Trojan horse experiments to reduce the uncertainties of the peak fitting procedures. This should lead to improved results for Γ_α and the derived stellar reaction rate $N_A\langle\sigma v\rangle$; however, such a study must remain beyond the scope of the present work.

The lowest resonances in the $^{16}O(n,\gamma)^{17}O$ *reaction.* At low energies the cross section of the $^{16}O(n,\gamma)^{17}O$ capture reaction is dominated by direct (nonresonant) *p*-wave capture to the $5/2^+$ ground state and $1/2^+$ first excited state of ^{17}O. The lowest resonances are found at 410.7 keV ($3/2^-$) and 941.7 keV ($3/2^+$). With $Q = 4143.08$ keV [12], these energies correspond to $E^* = 4554$ and 5085 keV.

The first resonance has an adopted width of $\Gamma = 40 \pm 5$ keV. Because of its spin $J = 3/2^-$, it does interfere with the direct capture amplitude, and thus it affects the capture cross section down to about 250 keV [5,27,28]. The second resonance with $J^\pi = 3/2^+$ cannot interfere with the direct *p*-wave capture. Although the adopted width of this second resonance is large ($\Gamma = 96 \pm 5$ keV), it has only very minor influence on the stellar reaction rate of the $^{16}O(n,\gamma)^{17}O$ reaction.

The present study provides total widths for the $3/2^-$ and $3/2^+$ states which are close to the adopted values. We find $\Gamma = 38.1 \pm 2.8$ keV for the $3/2^-$ state and 88 ± 3 keV for the $3/2^+$ state. Consequently, the adopted reaction rate of the $^{16}O(n,\gamma)^{17}O$ reaction [5,29] does not change significantly from the slightly revised widths of this study.

Further results. For 12 levels in ^{17}O the experimental width in the present study is given by the resolution of the experiment. The lowest state of the present study ($5/2^-$, 3843 keV) is located below particle thresholds, and thus a small width is obvious. For five states upper limits below 1 keV have been adopted; the present work confirms that these levels are narrow. For five further states small widths between 0.64 keV and 6.6 keV have been adopted. Again the present study confirms these adopted values. No width is available in Ref. [6] for the $11/2^-$ state at $E^* = 7757$ keV. The present work is able to give an upper limit of about 4 keV for the width, and we determine a slightly higher value of $E^* = 7763.6$ keV for the excitation energy.

There are four further states in ^{17}O with relatively broad widths which could be determined in this work. For three of these levels our new results for the widths are within 1σ of the adopted values [6]. For the relatively narrow ($\Gamma = 14.4 \pm 0.3$ keV) $7/2^-$ level at 7689 keV we find a slightly smaller width of 12 ± 4 keV. However, as the width of this level is smaller than our experimental resolution, the width from this work has larger uncertainties than the adopted value. For the broad $3/2^+$ level around $E^* \approx 7.2$ MeV we find a slightly higher $E^* = 7216$ keV and a slightly smaller width $\Gamma = 262 \pm 7$ keV with a significantly reduced uncertainty compared to the adopted $\Gamma = 280 \pm 30$ keV. The excitation energy of the $1/2^-$ state is reduced from $E^* = 5939 \pm 4$ keV to 5931.0 ± 1.1 keV, and the adopted width of $\Gamma = 32 \pm 3$ keV is confirmed by the present result of 33 ± 5 keV.

A surprising difference appears for the $3/2^-$ state with adopted $E^* = 5379.2 \pm 1.4$ keV and $\Gamma = 28 \pm 7$ keV. Here we find a higher excitation energy $E^* = 5388.8 \pm 0.6$ keV and a larger width $\Gamma = 39.0 \pm 2.1$ keV. We do not have an explanation for the difference of the excitation energy E^* between the present work and the adopted value which is based on the $^{16}O(d,p)^{17}O$ experiment by Piskor and Schäferlingova [30]. However, we note that the adopted width of $\Gamma = 28 \pm 7$ keV is based on an early $^{16}O(d,p)^{17}O$ experiment by Browne [31], whereas an early neutron scattering experiment by Striebel *et al.* [32] reports a much higher value of $\Gamma = 41.4$ keV (without given uncertainty).

It is interesting to note that an early experiment by Holt *et al.* [33] studied the $^{17}O(\gamma,n)$ reaction and deduced from the R-matrix analysis values for the width of five states in ^{17}O which coincide with our values within our error bars, if inflated by 30%. They unfortunately did not quote uncertainties. For the 6.36 MeV state they had a width of 130 keV.

Conclusions. The present work has used the $^{19}F(d,\alpha)^{17}O$ reaction to study excitation energies E^* and total widths Γ of levels in the ^{17}O nucleus at excitation energies between about 4 and 8 MeV. Several obtained widths have significantly smaller uncertainties than the adopted values [6]. The overall agreement with the adopted values [6] is good and remains typically within 1–2 σ of the adopted values.

The focus of the present study is the neutron production and absorption in the astrophysical *s* process. It is found that the role of ^{16}O as a neutron poison is not affected because the adopted widths of the first resonances in the $^{16}O(n,\gamma)^{17}O$ reaction are essentially confirmed in this work. The neutron production in the $^{13}C(\alpha,n)^{16}O$ reaction depends on the properties of the $1/2^+$ threshold level. Contrary to the adopted value of the excitation energy E^*, our new results show that this threshold level is located a few keV above the ^{13}C-α threshold, and we find a larger total width than adopted in Ref. [6] with a significantly reduced uncertainty.

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