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The "missing" 3^+ state of ^{18}Ne and explosive $^{17}F(p,\gamma)$ burning

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Wiescher, Görres, and Thielemann suggested that a "missing" $J^\pi = 3^+$ level in ^{18}Ne should occur at $E_x \approx 4.33$ MeV, only $\approx$410 keV above the ^{17}F+p threshold. They noted that this level would provide an s-wave resonance in the $^{17}F(p,\gamma)$ reaction, greatly increasing its thermonuclear reaction rate. This, in turn, would have a pronounced effect on the production of ^{17}O and ^{18}O in explosive stellar environments. We have searched for this level using the $^{16}O(^3He,n)$ reaction. High-resolution time-of-flight spectra show that the 3^+ level occurs at $E_x = 4.561 \pm 0.009$ MeV, $\approx$230 keV higher than suggested. The astrophysical consequences of this result are discussed.

I. INTRODUCTION

Wiescher, Görres, and Thielemann[1] have noted that a $J^\pi = 3^+$ level is expected to occur in ^{18}Ne slightly above the ^{17}F+p threshold, and that this level would form a strong s-wave resonance in the $^{17}F(p,\gamma)$ reaction. This resonance could have a profound effect on the thermonuclear $^{17}F(p,\gamma)$ rate, altering the "hot" CNO cycle in a manner that has a decisive influence on the abundances of ^{17}O and ^{18}O, which are produced by the β decays of ^{17}F, ^{18}F, and ^{18}Ne. The effect of the 3^+ level, however, depends critically upon its energy with respect to the ^{17}F+p threshold. In this paper, we present measurements that locate the 3^+ level and then discuss the implications of our result for explosive nucleosynthesis.

II. THEORETICAL ESTIMATES OF THE EXCITATION ENERGY

The isospin analog of the ^{18}Ne 3^+ level is known to occur in ^{18}O at 5.3778 ± 0.0012 MeV (see Fig. 1).[2] Thus to predict its excitation energy in ^{18}Ne one need only account for the Coulomb energy shift. This shift (sometimes called the Thomas-Ehrman shift) is expected to be very large because the 3^+ level has an open s-wave decay channel to p+^{17}F. Wiescher, Görres, and Thielemann estimated the excitation energy of the 3^+ level by two independent methods: an R-matrix calculation and a simplified shell-model computation. They predicted E_x=4.31 and 4.33 MeV by these two approaches and noted that these values lie sufficiently close to the ^{17}F+p threshold that the 3^+ resonance would greatly enhance the $^{17}F(p,\gamma)$ reaction rate.

Brown[3] has made a more elaborate estimate of the Coulomb energy shift using the charge-dependent single-particle energies and two-body matrix elements from Ormand and Brown's shell-model analysis[4] of Coulomb energies of the A=10 to 55 nuclei. He predicts E_x=4.47 MeV.

We estimate the excitation energy of ^{18}Ne(3^+) by the following approach. Shell-model calculations[3,5] and experiment[6] both indicate that the spectroscopic factor for ^{18}Ne(3^+) $\to$^{17}F(g.s.)+p is essentially unity. Therefore we generate the 3^+ level wave functions as an optical model $2s_{1/2}$ resonance (or, for ^{18}O, as a bound state) in the channel consisting of the A=17 ground state plus a nucleon. The optical potential is a charge-independent Woods-Saxon well to represent the strong interaction, plus the Coulomb potential associated with the proton in the electric field of a uniformly charged A=17 ground state (assumed to have a Woods-Saxon shape consistent with the results of elastic electron scattering by ^{17}O). The depth of the strong interaction well is adjusted to produce the 3^+ bound state in ^{18}O at the correct excitation energy. Then the excitation energy (defined as the point at which the phase shift $\delta = 90°$) and width (defined as $\Gamma_p = 2[d\delta/dE(\delta = 90°)]^{-1}$) of the 3^+ state in ^{18}Ne are determined by the computed $\delta(E)$ for ^{17}F+p. This calculation yields E_x=4.53 MeV and Γ_p=22 keV. We expect our estimate to be more realistic than the other two because it incorporates more information about the A=18 system than that of Ref. 1 but is not affected by global averaging as is the calculation of Brown. If our estimate is correct, the influence of the 3^+ resonance will be considerably smaller than predicted by Wiescher, Görres, and Thielemann.

III. STUDY OF THE $^{16}O(^3He,n)$ REACTION

A. Motivation

There are only a few possibilities for producing ^{18}Ne in a fashion that permits high-resolution spectra. The most obvious production reactions are $^{16}O(^3He,n)$ and

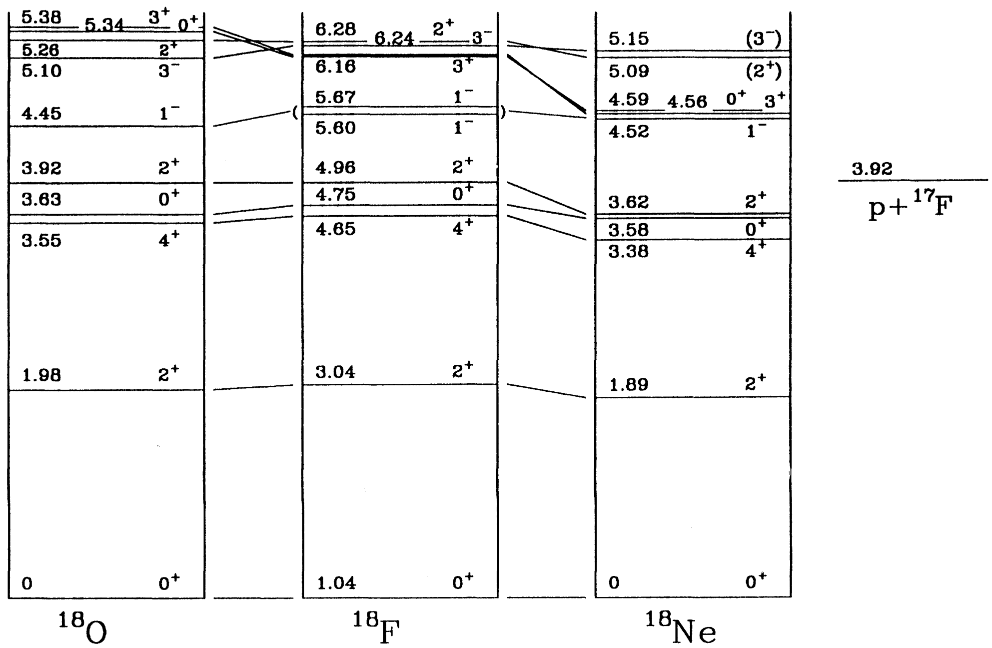

FIG. 1. Level diagram of the A=18 nuclei, showing the resonances in ^{17}F+p that are expected to dominate the burning rate. The ^{18}Ne 3^+ level is from this work; other levels are taken from the compilation of Ref. 2.

^{20}Ne(p, t). However, neither of these reactions is ideally suited to populate the 3^+ level because their dominant reaction mechanisms, two-proton or two-neutron transfer, do not populate unnatural parity states. We selected the ^{16}O(^{3}He, n) reaction because the isospin analog of the 3^+ level is populated with reasonable intensity[7] (presumably by complicated multistep processes) in the isospin mirror reaction ^{16}O(t, p). We therefore expected to populate the ^{18}Ne 3^+ level by taking data at bombarding energies close to the 10 MeV value used in the (t, p) study.

B. Apparatus

The experiments were performed using the University of Washington pulsed-beam time-of-flight (TOF) spectrometer. ^{3}He beams from a duoplasmatron ion source were bunched and chopped into 0.8-ns-long bursts at a repetition rate of 4.14 MHz, and accelerated by an FN tandem accelerator. Neutrons were detected in 12.7-cm-diam BC501 liquid scintillators of 2.6 or 5.1 cm thickness. These allowed us to distinguish neutrons from γ rays on the basis of the anode pulse shape. Each detector drove a constant-fraction discriminator that provided the START pulse for a time-to-amplitude converter (TAC). The STOP pulse was derived from a resonant cavity on the beam line that sensed the ^{3}He beam bursts. Three signals were recorded for each detector—its TAC output, the output of an analog pulse-shape discriminator circuit, and the pulse height. Data were recorded in event mode and analyzed off line with cuts on the pulse shape and pulse height optimized for best n-γ discrimination. "Time slewing" in the constant-fraction discriminator was corrected in software by adding to the TAC signal a term linear in the pulse height.

Target contamination was a major concern because the 3^+ level was expected to be weakly populated. Fortunately, any contaminants could be readily identified because ^{16}O(^{3}He,n) has the most negative Q value of *any* (^{3}He,n) reaction, so that contaminants *must* produce neutrons with higher energy than those from ^{16}O(^{3}He,n_0). Oxygen targets in the form of Ta_2O_5 were prepared by anodizing 0.13-mm-thick high-purity Ta blanks in 0.1N sulfuric acid. Target thicknesses (typically 150 μg/cm^2) were determined by the voltage drop in the anodization process.[8] At our bombarding energies neutron yield from the tantalum was negligible. The targets were mounted in a Ta-lined Pyrex tee at the end of a clean cryo-pumped vacuum system operating at pressures below 5×10^{-7} Torr. To avoid any residual C buildup, we periodically (1 h intervals) moved the target so that the beam struck a "fresh" surface. With these precautions, contaminants were reduced to a negligible level, the only detectable contaminant being ^{12}C. Its effect on our spectra was determined by always taking data with a C target under the same kinematic conditions as the ^{16}O(^{3}He, n) data.

C. Results

Because Wiescher, Görres, and Thielemann had predicted that the 3^+ level should occur at $E_x \approx 4.33$ MeV, we first made careful high-statistics searches for any structure in this region. We took data at 7 different bombarding energies between 9.50 and 10.50 MeV and at angles of 0°, 42°, and 126° to allow for the possibility that the cross section for producing the 3^+ state could be a strong function of energy, and to take advantage of the fact that the energy resolution of TOF spectra is best when the neutrons have low velocities. As can be seen in Fig. 2, no statistically significant ^{18}Ne peaks were observed at excitation energies between 3.7 and 4.5 MeV.

Next we scanned the region above the 4.5 MeV "doublet" in runs at bombarding energies of 10.5, 11.0, and 12.0 MeV with detectors at angles between 0° and 35°. Again, no statistically significant peaks were seen between E_x=4.60 and 5.08 MeV.

Finally, we studied the 4.5 MeV "doublet" with the best possible resolution, to see if the 3^+ level could lie there. Data were taken with detectors at $\theta_n = 0°$ and $\theta_n = 124.7°$. Flight paths were chosen so that in each detector the times of flight for neutrons from the 4.5 MeV "doublet" were close to the maximum practical value (the 242-ns beam burst period). Time resolution was optimized by rotating the 124.7° detector in the horizontal plane through an angle such that the variation of neutron velocity across the finite angular range of the detectors was compensated by a corresponding change in flight path. The results of a 24-h-long run at an average beam current of 270 nA are shown in Fig. 3. The smooth curves are line-shape fits to the TOF spectra which incorporate all previously known[2] levels of ^{18}Ne. These line shapes included the following factors:

(1) The known contributions to *time* resolution from the electronics and beam-burst durations, approximated by a Gaussian with small exponential tails whose parameters were fixed by the shape of the prompt γ peak. (The Gaussian accounts for the electronic time resolution and the beam-burst duration, while the tails account for the effect of the buncher on the "wings" of the beam burst.)

(2) The known thickness of the scintillator, approximated by a rectangular *time* resolution function whose width was determined by the scintillator thickness and the neutron velocity.

(3) The known target thickness, approximated by a rectangular *energy* resolution function.

(4) A function to account for scattering of the neu-

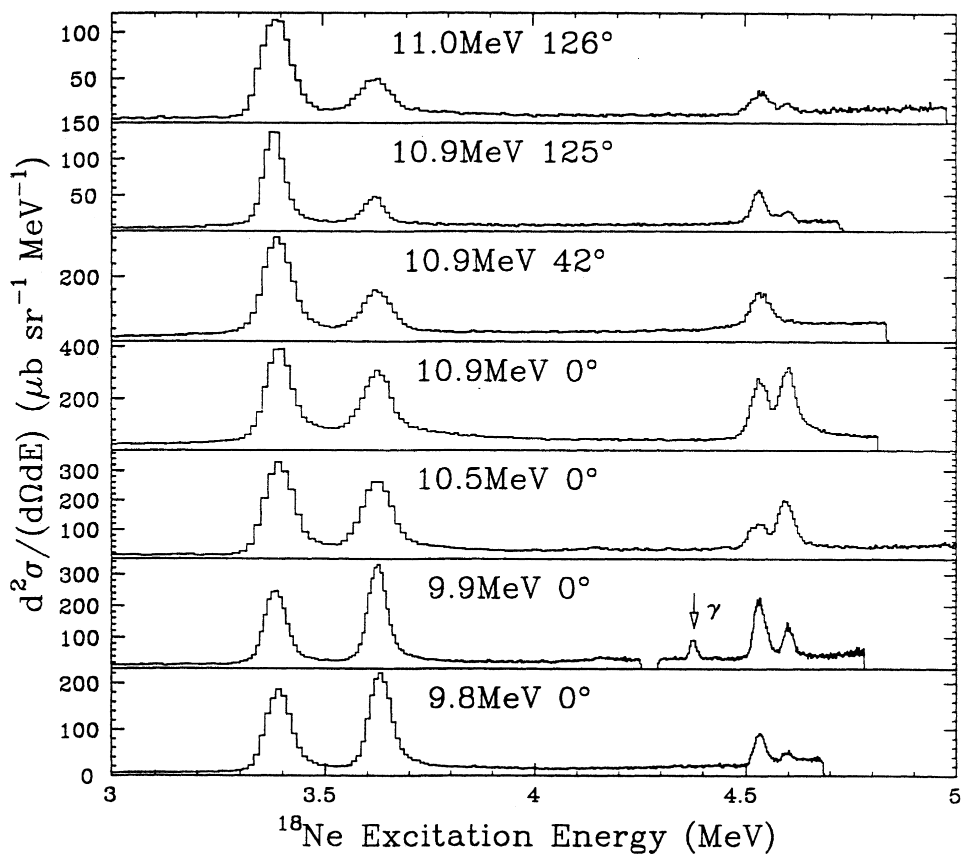

FIG. 2. Searches for ^{18}Ne structure at $E_x \approx 4.33$ MeV. TOF spectra taken under a variety of kinematic conditions have been transformed so that the horizontal axis is excitation energy in ^{18}Ne. The vertical axis is in cross-section units but the neutron detector efficiency was approximated by a constant within each spectrum. In the 9.9 MeV 0° spectrum, the 4.5 MeV doublet had such a long TOF that the TAC scale "wrapped around." This accounts for the gap in the middle of the spectrum and the small peak from prompt γ rays that were misidentified as neutrons.

trons by material in the target chamber and detector support, approximated by a pair of exponential tails on the long TOF side of the *time* spectra. The parameters of the scattering tails were fixed by calibration reactions that produced isolated, sharp neutron groups at energies ranging from 1 to 6 MeV. These parameters were found to be slow functions of neutron energy, and to depend on the detector location (this was expected as the 0° detector was located in a hole in a cement wall while the 124.7° detector was supported on a low-mass stand).

It is apparent that the 0° spectrum in Fig. 3 is well fitted by the previously known levels of ^{18}Ne, but the 124.7° spectrum shows clear evidence for a previously unresolved level lying between the known E_x=4.52 and E_x=4.59 MeV states. This is consistent with the ^{16}O(t, p) results[7] where the angular distribution of the 3^+ group showed a pronounced backward peak at $\theta_{c.m.} \approx$ 120°. This peak cannot be due to a target contaminant and must correspond to a level of ^{18}Ne as the only observable contaminant was ^{12}C and runs with a carbon target demonstrated that ^{12}C(^{3}He, n) cannot account for our new level (see Fig. 3). Because analogs of all other ^{18}O levels below E_x=6.0 MeV have already been seen in the ^{16}O(^{3}He, n) reaction, we conclude that the new level corresponds to the 5.378 MeV level of ^{18}O and has $J^\pi = 3^+$.

The excitation energies of the 3^+ level and the nearby 1^- and 0^+ states were determined from our spectra by a comparison technique that minimized any errors due to uncertainties in the calibrations of the time scales and of the beam-energy analyzing magnet. Immediately after the ^{16}O(^{3}He, n) spectra were obtained, we switched the beam from ^{3}He to ^{4}He *without changing the beam-energy analysis system in any way*, installed an enriched ^{13}C target, and took ^{13}C(α, n) spectra. The 6.917 and 7.117 MeV states of ^{16}O produced neutron groups with energies very close to those from the ^{18}Ne doublet (see Fig. 4). As

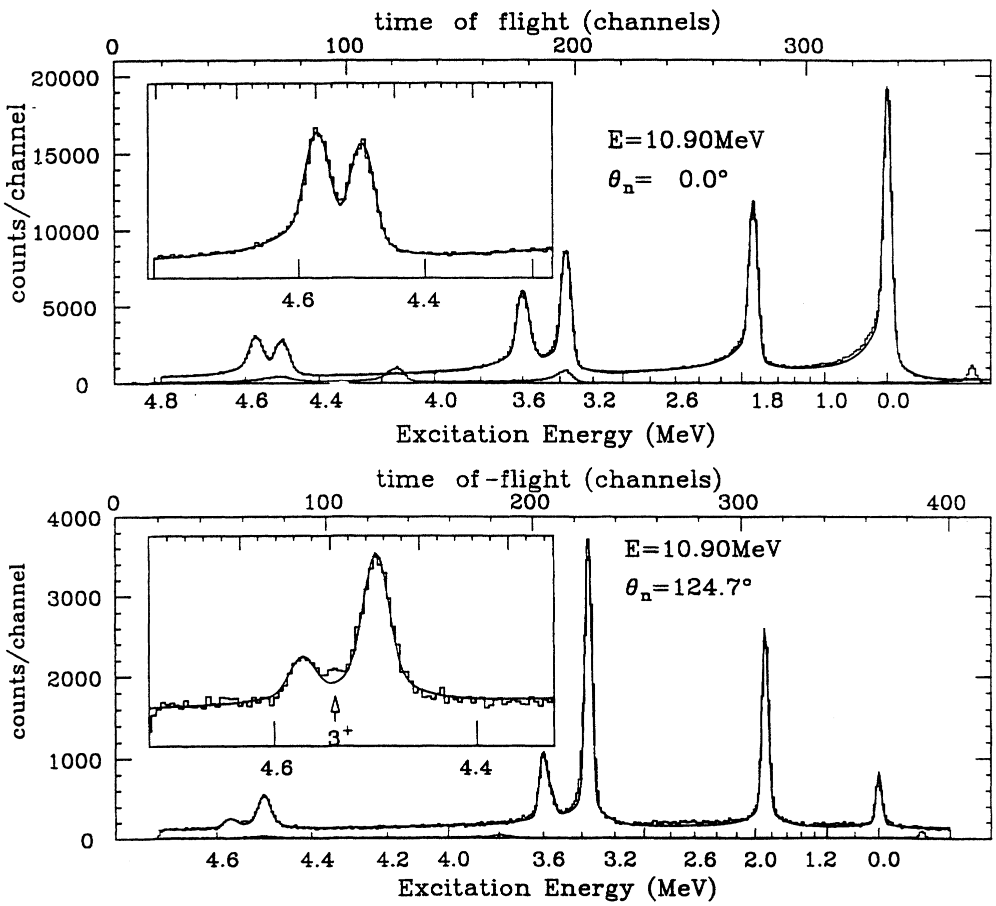

FIG. 3. Neutron TOF spectra for the ^{16}O(^{3}He, n) reaction at $E_{^3\mathrm{He}}$ = 10.90 MeV. Upper and lower panels for detectors at $\theta_n = 0°$ and $\theta_n = 124.7°$, respectively. The 0° detector had a thickness of 5.1 cm and a flight path of 4.53 m; the 124.7° detector had a thickness of 2.5 cm and a flight path of 2.93 m. Insets show the region around $E_x \approx 4.5$ MeV. The curves are fits to the data using line shapes corresponding to the previously known levels at 0.000, 1.887, 3.376, 3.576, 3.616, 4.519, and 4.590 MeV. In the 124.7° spectrum, an excess of counts attributable to the 3^+ level at 4.56 MeV is evident (the excess counts at $E_x \leq 3.0$ MeV are accounted for by the 0.2% abundance of ^{18}O in the target). Each panel also shows a (^{3}He, n) spectrum taken with a natural carbon target under exactly the same conditions.

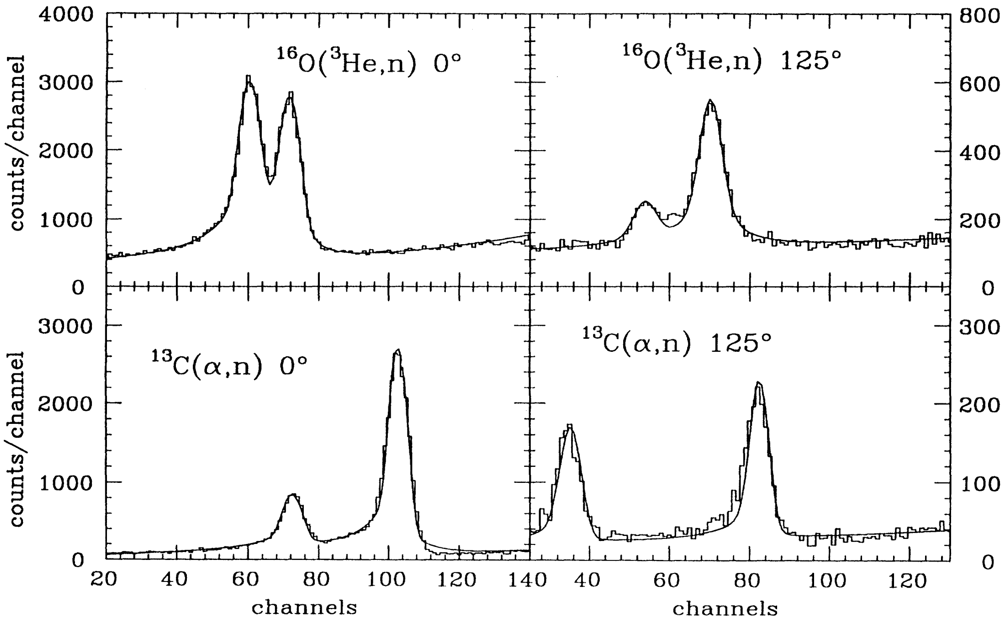

FIG. 4. TOF spectra used to calibrate the excitation energy scale and neutron tails. Upper panels: ^{16}O(^{3}He, n) data at 0° and 124.7°. Lower panels: ^{13}C(^{4}He, n) data taken without changing the detectors or energy analyzing magnet in any way. The ^{13}C target thickness was chosen so as to have the same beam-energy loss as in the ^{16}O(^{3}He, n) measurement.

these levels had (α, n) Q values with negligible uncertainties (± 0.6 keV), they provided a convenient calibration of the Q value scale. We determined that the 3^+ level has a Q value of $-7757 \pm 6 \pm 5$ keV. The first error is the statistical uncertainty in locating the centroid of the 3^+ peak. The second error reflects the uncertainties in the beam energy and time scales that were evaluated as follows. The time scales were calibrated by temporarily turning off the 4.13 MHz chopper (that normally eliminated two out of every three pulses of the 12.40 MHz buncher) to produce TOF spectra with three prompt γ peaks separated by 80.643 ns. The ^{13}C(α, n) spectra shown in the lower panels of Fig. 4 were then fitted with these TAC calibrations fixed, but allowing the beam energy to float. The best fit was obtained with a beam energy that agreed with the nominal value to within 1 keV. Then the TAC scales were changed by $\pm 1\sigma$, and the change in the calibration constant of the energy-analyzing magnet required to maintain a good fit was found. The 5 keV ^{16}O(^{3}He, n) Q-value scale error is the variation that corresponded to these correlated changes in calibration constant and time scales, including $\pm 10\%$ uncertainties in the target thicknesses.

Adopting[2] a ^{18}Ne mass excess of 5319 ± 5 keV, we infer an excitation energy $E_x(3^+) = 4.561 \pm 0.009$ MeV, in good agreement with our prediction, and about 230

TABLE I. Energies and widths of low-lying ^{18}Ne levels.

	Previous results (Ref. 2)		This work		
J^π	E_x (keV)	Γ (keV)	Q (keV)	E_x (keV)	Γ (keV)
0^+	0		-3196^a	0^a	
2^+	1887.3±0.2		-5083^a	1887^a	
4^+	3376.2±0.4		-6572^a	3376^a	
0^+	3576.3±2.0		-6772^a	3576^a	
2^+	3616.4±0.6		-6812^a	3616^a	
1^-	4519 ±8	≤20	$-7716\pm1\pm5^b$	$4520\pm1\pm7^{b,c}$	9±6
3^+			$-7757\pm6\pm5^b$	$4561\pm6\pm7^{b,c}$	25^d
0^+	4590 ±8	≤20	$-7785\pm1\pm5^b$	$4589\pm1\pm7^{b,c}$	4±4

[a]These levels, along with ^{16}O states fed in ^{13}C(α, n), were used for calibration.

[b]The first uncertainty is statistical; the second refers to uncertainties in the time-of-flight and beam-energy scales.

[c]Excitation energies were computed using a ^{18}Ne mass excess[2] of 5319±5 keV.

[d]Estimated from a Woods-Saxon calculation.

keV higher than the estimate of Wiescher, Görres, and Thielemann. Results for all three levels are summarized in Table I. Our E_x and Γ values for the 1^- and 0^+ levels agree with previous work,[9,10] but are more precise. The observed widths of the 1^- and 0^+ levels are consistent with zero, and with the values $\Gamma(1^-) < 0.1$ keV and $\Gamma(0^+) = 1.0$ keV inferred by multiplying the observed spectroscopic factors[6] in ^{18}O by optical model calculations of the appropriate single-particle widths; decays to the ^{17}F first excited state are expected to be negligible.

IV. ASTROPHYSICAL IMPLICATIONS

The astrophysical importance of the 3^+ level lies in its role as a resonance in $^{17}\mathrm{F}(p,\gamma)$, a reaction that plays a dominant role in the nucleosynthesis of ^{17}O and ^{18}O in hot stellar environments. To assess the influence of this level, one needs (in decreasing order of importance) the following.

(1) The excitation energy E_x. The energy is easily the most important of these parameters because the astrophysical reaction rate depends approximately exponentially upon the energy but only approximately linearly on the widths.

(2) The gamma width Γ_γ. The analog 3^+ level in ^{18}O decays by $M1$ transitions to the two low-lying 2^+ states. Experiment[2] provides only *lower* limits of 19 and 3 meV for the γ widths of the ^{18}O ($3_1^+ \rightarrow 2_1^+$) and ($3_1^+ \rightarrow 2_2^+$) transitions; therefore we must resort to shell-model calculations[3] of the γ widths. Brown[3] predicts ^{18}Ne γ widths of $\Gamma_\gamma(3_1^+ \rightarrow 2_1^+) = 21$ meV, $\Gamma_\gamma(3_1^+ \rightarrow 2_2^+) = 3.4$ meV, and $\Gamma_\gamma(3_1^+ \rightarrow 4_1^+) = 0.8$ meV. For purposes of estimating the stellar reaction rate, we adopt the values $\Gamma_\gamma(3_1^+ \rightarrow 2_1^+) = 25 \pm 16$ meV, $\Gamma_\gamma(3_1^+ \rightarrow 2_2^+) = 3.8 \pm 3.1$ meV, and $\Gamma_\gamma(3_1^+ \rightarrow 4_1^+) = 0.8 \pm 0.8$ meV, where the lower bounds are obtained from the ^{18}O experimental results [we assume that the ^{18}Ne $B(M1)$'s are identical to those in ^{18}O] and the upper bounds are obtained by assuming that the actual $B(M1)$ could be twice as large as the shell-model prediction.

(3) The $^{17}\mathrm{F}(p,\gamma)$ direct-capture amplitudes. There are no $E1$ direct capture amplitudes from initial s-wave states, and p-wave direct capture does not interfere with the 3^+ resonant amplitude. We computed the $^{17}\mathrm{F}(p,\gamma)$ direct capture cross section using the formalism and $^{17}\mathrm{O}(p,\gamma)$ direct-capture spectroscopic factors of Rolfs[11] and the appropriate dipole charges for the $^{17}\mathrm{F}+p$ system. (The dominant transitions are $R \rightarrow 2_1^+$ and $R \rightarrow 2_2^+$.) We find $S \approx S_0 + S_1 E + S_2 E^2$, where $S_0 = (2.9 \pm 0.4) \times 10^{-3}$ MeV b, $S_1 = (-1.3 \pm 0.2) \times 10^{-3}$ b, and $S_2 = (4.7 \pm 1.1) \times 10^{-4}$ b MeV^{-1}. Our adopted uncertainties reflect an assumed 25% uncertainity in the direct-capture spectroscopic factors.

(4) The proton width Γ_p. This may be reliably calculated from E_x as the spectroscopic factor $S \simeq 1$. The optical model described above predicts $\Gamma_p = 25$ keV. Because $\Gamma_p \gg \Gamma_\gamma$ a small uncertainty in Γ_p has a negligible effect on the predicted reaction rate.

(5) The properties of the nearby 1^- and 0^+ resonances. We take the energies of these resonances from

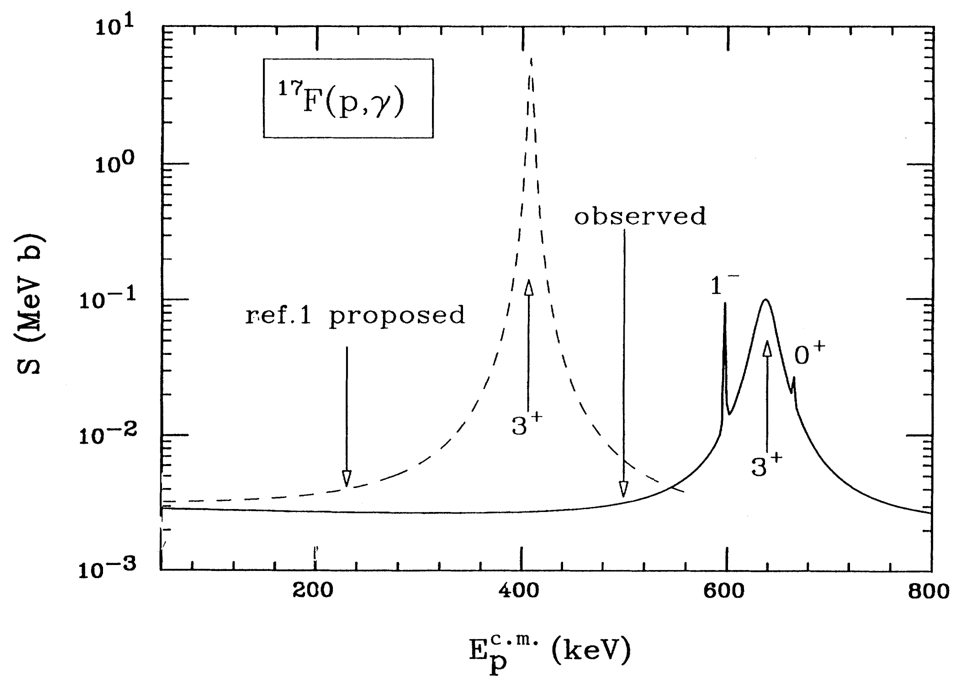

FIG. 5. Deduced S factor for the $^{17}\mathrm{F}(p,\gamma)$ reaction. Dashed curve: Wiescher, Görres, and Thielemann prediction based on their estimate of $E_x(3^+)$=4.33 MeV. Solid curve: our prediction based on the experimental value of $E_x(3^+)$=4.56 MeV.

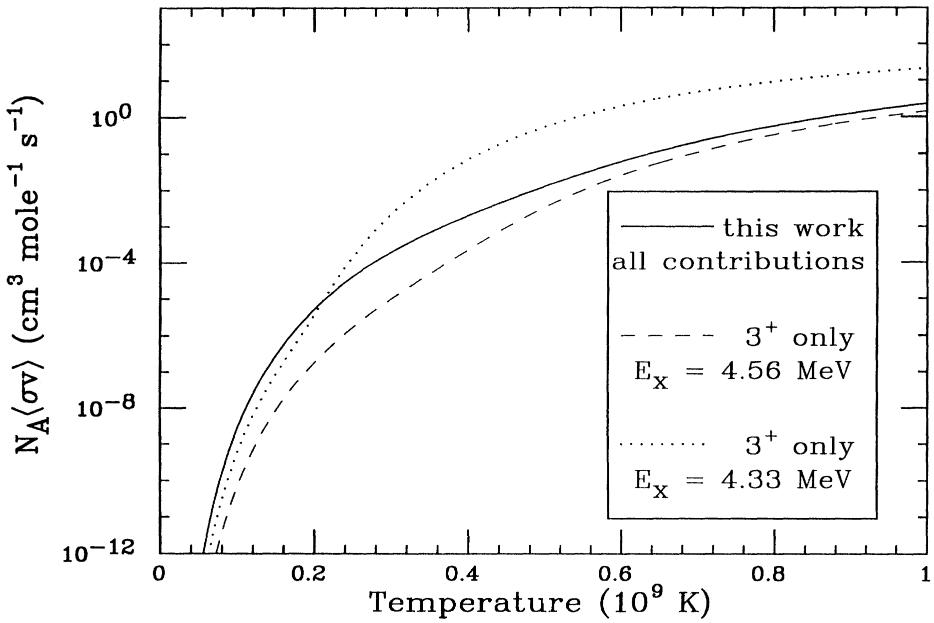

FIG. 6. The $^{17}F(p,\gamma)$ reaction rate as a function of temperature. The solid line is based on our parameters of the 3^+, 1^-, and 0^+ resonances plus direct capture computed as described in the text. The dashed (dotted) lines show the contributions of the 3^+ resonance at the observed (previously expected) excitation energy.

our measurements, and the total widths from the observed ^{18}O spectroscopic factors as described above. We infer $\Gamma_\gamma(1_1^-) = 15 \pm 3$ meV and $\Gamma_\gamma(0_3^+) = 1.0 \pm 0.2$ meV, by assuming that these ^{18}Ne decays have the same reduced transition strengths as the analogous transitions in ^{18}O.

Our inferred $^{17}F(p,\gamma)$ S factor is shown in Fig. 5; the corresponding reaction rates are given in Fig. 6 and Table II.

Wiescher, Görres, and Thielemann predicted that the 3^+ resonance would enhance the $^{17}F(p,\gamma)$ reaction rate by two orders of magnitude over the contribution of the nearby 1^- and 0^+ levels. This had interesting implications for a proposed explanation[12] of the astonishing observation[13–15] of roughly four solar masses of ^{26}Al near the center of our Galaxy. Hillebrandt, Thielemann, and Langer[12] showed that the explosion of a supermassive star (10^5 solar masses) could produce the required amount of ^{26}Al. Their model also accounted for the high abundance ratios of $^{13}C/^{12}C$ and $^{14}N/^{15}N$ that are observed[16,17] in dense clusters near the galactic center. However, their predicted $^{17}O/^{18}O$ ratio was about two orders of magnitude larger than the solar value, in contradiction to observations. This apparently ruled out a supermassive star explosion as an explanation for the ^{26}Al abundance. However, Wiescher, Görres, and Thielemann showed that if the reaction chain used in Ref. 12 were modified to include the contribution of a ^{18}Ne 3^+ level at $E_x \simeq 4.33$ MeV, then the supermassive star model would be in agreement with all observations.

TABLE II. Predicted rate[a] of the $^{17}F(p,\gamma)$ reaction.

T (10^9 K)	$N_A\langle\sigma v\rangle$ (cm^3 mole^{-1} s^{-1})
0.1	$(2.81 \pm 0.45) \times 10^{-9}$
0.2	$(5.28 \pm 0.87) \times 10^{-6}$
0.3	$(1.98 \pm 0.33) \times 10^{-4}$
0.4	$(2.04 \pm 0.33) \times 10^{-3}$
0.5	$(1.29 \pm 0.24) \times 10^{-2}$
0.6	$(6.04 \pm 1.60) \times 10^{-2}$
0.7	$(2.10 \pm 0.72) \times 10^{-1}$
0.8	$(5.63 \pm 2.22) \times 10^{-1}$
0.9	1.23 ± 0.51
1.0	2.29 ± 0.98

[a]Uncertainties in the rates were computed as described in the text.

Our discovery of the 3^+ level at an energy approximately 0.2 MeV higher than calculated by Wiescher, Görres, and Thielemann causes the contribution of the 3^+ resonance to the $^{17}F(p,\gamma)$ reaction rate to be about two orders of magnitude smaller than they expected. Thus Wiescher, Görres, and Thielemann's resurrection of the supermassive star explosion scenario as an explanation for the enormous mass of ^{26}Mg observed in the center of our Galaxy is not viable, as the model still fails to predict the observed $^{17}O/^{18}O$ ratio.

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