Properties of states at 7–8 MeV in ^{18}Ne

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We present calculated values of energies and widths for astrophysically interesting states at 7–8 MeV excitation energy, based—whenever possible—on information from mirror levels in ^{18}O.

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With a ^{17}F beam Harss *et al.* [1–3] investigated the reactions ^{17}F(p,α), ^{17}F(p,p), and ^{17}F(p,p') in ^{18}Ne. In stellar explosions, the reaction ^{14}O$(\alpha,p)^{17}$F proceeds through these resonances—first through the 1^- at $E_x=6.15$ MeV, and then (above about 2×10^9 K) through several resonances above an excitation of 7 MeV. The 1^- contribution is uncertain because its strength is poorly determined—$\omega_\gamma(p,\alpha)=0.8^{+1.2}_{-0.5}$ eV. Uncertainties for the states above 7 MeV are also quite large—as summarized in Table I (taken from information in Table II of Ref. [1]) . We have performed calculations of the energies and widths using information from the parent states in ^{18}O whenever appropriate. A preliminary version of some of our results has appeared previously [4].

The information in Table I is primarily from Refs. [1,2], with some input from other work. Harss *et al.* performed a difficult experiment with a radioactive ^{17}F beam and measured the quantities of direct astrophysics interest viz., $\omega_\gamma(p,\alpha)$. Decays of the various resonances to excited states of ^{17}F are of interest because the reaction ^{14}O(α,p) can also proceed through excited final states. It is also important to know if any of the resonances decay to unbound levels of ^{17}F, because, if so, that would deplete ^{14}O but not produce ^{17}F. In a preliminary experiment [2], Harss *et al.*, located three resonances at excitation energies of 7.16 ± 0.15, 7.35 ± 0.06, and 7.60 ± 0.05 MeV. From their comparisons with mirror levels, they tentatively assigned $J^\pi=1^-$ to the 7.17-MeV state, 4^+ or 1^- for 7.37, and 1^- or 2^+ for 7.60. We suggested [4] that the lower one was 4^+ and the upper was 1^-, based on comparison to mirror levels in ^{18}O and our calculations. We made no prediction for 7.37, other than that it was unlikely to be 1^- (or 4^+). In fact the 7.37-MeV level puzzled us because we found no candidate for its mirror among the known levels of ^{18}O. In a new experiment and careful analysis [1], the same group now agrees with us as to the J^π of the first and third of these three levels. For 7.37, they make no J^π assignment from their data (other than it must be natural parity), but by inspection of the levels of ^{18}O they conclude that the nearest known level that could be its mirror is at 8.21 MeV—a 2^+ state. But nothing in their data favors 2^+ over any other natural-parity assignment. (Of course, very high J could also be ruled out, on penetrability arguments.) As the 4^+ assignment for the 7.05-MeV level and 1^- for 7.60 now appear firm, we discuss their properties first.

Harss *et al.* [1] have now proven that ^{18}Ne(7.05) has $J^\pi=4^+$. They conclude that it is the analog of ^{18}O(7.11), as suggested previously by us [4], and even earlier by Hahn *et al.* [5]. Its expected energy in ^{18}Ne is 7.086 ± 0.040 MeV [6]. With our geometrical parameters ($R=3.37$ fm, $a=0.60$ fm), the width of 91 ± 13 meV in ^{18}O results in an α spectroscopic factor of 0.303 ± 0.055 [7]. For an excitation energy of 7.05 MeV in ^{18}Ne, the single-particle (sp) α width calculated with the same geometrical parameters is 63 eV, giving [using $\Gamma_\alpha(\mathrm{expt})=40\pm14$ eV] $S_\alpha(^{18}\mathrm{Ne})=0.619\pm0.235$, much larger than in ^{18}O. In the first paper of Harss *et al.*, this resonance energy was 7.16 ± 0.15. Hahn *et al.* [5], see two states—at 7.05 and 7.12 MeV. The newest paper of Harss *et al.*, provides $E_x=7.05\pm0.10$ MeV. The experimentally determined (p,α) strength is $0.75\,\Gamma_p\Gamma_\alpha/\Gamma=29\pm10$ eV. With $\Gamma_p\approx\Gamma$, the result for Γ_α is 39 ± 13 eV. Of course, these uncertainties on E_x and Γ_α are presumably one σ values, so the true E_x and Γ_α could easily lie outside those uncertainties. If the ^{18}Ne 4^+ excitation energy is 7.05 MeV, our best estimate of the expected α width is 19 ± 4 eV, whereas if $E_x=7.15$ MeV we get $\Gamma_\alpha(\mathrm{sp})=110$ eV and hence $\Gamma_\alpha=34\pm7$ eV.

Because S_α comes from the dominant component of the wave function, and is close to the maximum allowed for that configuration, it is stable to small configuration mixing. Thus, even with some small amount of isospin violation, the assumption $S_\alpha(^{18}\mathrm{Ne})=S_\alpha(^{18}\mathrm{O})$ should still be valid. Then we can actually bypass the computation of S_α and its dependence on geometry and write directly

$$\Gamma_{\mathrm{calc}}(^{18}\mathrm{Ne})=[\Gamma_{\mathrm{sp}}(^{18}\mathrm{Ne})/\Gamma_{\mathrm{sp}}(^{18}\mathrm{O})]\Gamma_{\mathrm{expt}}(^{18}\mathrm{O}).$$

TABLE I. Properties of states at 7–8 MeV in ^{18}Ne.

E_x (MeV)	J^π	Γ (keV)	$\omega_\gamma(p,\alpha)$ (eV)	Γ_α (eV)	$E_x(^{18}\mathrm{O})$ (MeV)
7.05 ± 0.10	4^+	90 ± 40	29 ± 10	40 ± 14	7.11
7.37 ± 0.06	2^+?	70 ± 60	18 ± 14	40 ± 30	8.21?
	0^+?			200 ± 150	(7.02)?
7.60 ± 0.05	1^-	75 ± 20	255 ± 30	1000 ± 120	7.62
7.71 ± 0.05	2^-	70 ± 30	[a]	[a]	7.77

[a]Unnatural parity forbids α channel; has $\Gamma_{p_0}=59\pm25$ keV, $\Gamma_{p_1}=11\pm5$ keV.

TABLE II. Properties of the 4_2^+ state in ^{18}O and ^{18}Ne.

Quantity	^{18}O	^{18}Ne	
		Expt.[a]	Calculated
E_x (MeV)	7.11	7.05 ± 0.10	7.086 ± 0.04[b]
Γ_α (eV)	$(91\pm13)\times10^{-3}$	39 ± 13	22.6 ± 3.2[c]
Γ_p (keV)		90 ± 40	64 ± 13[c]
S (nucleon)	0.18 ± 0.04	0.25 ± 0.11[d]	

[a]Reference [1].
[b]Reference [6].
[c]Computed assuming mirror symmetry of spectroscopic factors.
[d]Computed from measured width and our calculated sp width.

TABLE III. Properties of the 1_3^- state in ^{18}O and ^{18}Ne.

Quantity	^{18}O[a]	^{18}Ne	
		Expt.[b]	Calculated
E_x (MeV)	7.1616	7.60 ± 0.05	7.55–7.75[c]
Γ_α(keV)	<2.5	1.02 ± 0.12	<18[d]
Γ_p (keV)		72 ± 20	
S (nucleon)		$(0.03\pm0.01)\ p_0$[e] $<1.2\times10^{-3} p_1$[e]	

[a]Reference [19].
[b]Reference [1].
[c]Present work: weak coupling, plus Coulomb.
[d]Assuming mirror symmetry.
[e]Calculated from measured widths (Ref. [1]) and our sp widths.

Even if the individual Γ_{sp} are sensitive to values of r_0 and a of the potential well, the ratio of sp widths is much less so. This method gives $\Gamma_{calc}(^{18}\mathrm{Ne})=22.6\pm3.2$ eV for a 4^+ state at 7.05 MeV. If its energy is 7.15 MeV, this changes to 38.2 ± 5.4 eV. These uncertainties do not include any contribution from the assumption of equal α strengths in the mirror nuclei. We know of no serious, quantitative attempts to assess the reliability of this assumption, but (for reasons noted above) we expect it to be especially valid in the present case.

The proton width of 90 ± 40 keV for the state is reasonable. The parent state in ^{18}O has a neutron spectroscopic factor of 0.18. For $p+{}^{17}$F, with $r_0=1.25$ fm, $a=0.65$ fm, we get $\Gamma_p(\mathrm{sp})=357$ keV, resulting in $S_p=0.25\pm0.11$. Or, using the S_n from ^{18}O (with an uncertainty of 20%) would give $\Gamma_p=64\pm13$ keV, consistent with the measured value, but more precise. Again, this uncertainty does not include any uncertainty arising from the assumption $S_p=S_n$ for mirror nuclei.

We agree with Harss *et al.* [1] that ^{18}Ne(7.60) is likely to be the analog of ^{18}O(7.616,1^-). Their argument (and ours [4]) is based on the expected small shift in excitation energy for negative-parity states in this excitation-energy region—because they are primarily single hole in character (discussed further below). The shape of their angular distribution allows 1^-, 2^+, 3^-, or 4^+. In ^{18}Ne, the α width is 1.02 ± 0.12 keV, and our calculated α single-particle width is 112 keV, giving $S_\alpha=9.1\times10^{-3}$. In ^{18}O the single-particle α width for the 1^- state at 7.616 MeV is 15.3 keV, so that if S_α is the same for the mirror, we would expect $\Gamma_\alpha(1^-, 7.616\ \mathrm{MeV})=0.14\pm0.02$ keV in ^{18}O, well within the present limit of $\Gamma_\alpha(\mathrm{expt})<2.5$ keV. The experimental ground-state (g.s.) proton width of 72 ± 20 keV in ^{18}Ne corresponds to $S_p=0.03\pm0.01$ for ^{17}F(g.s.), and the limit of $\Gamma_{p_1}<2$ keV results in $S_p<1.2\times10^{-3}$ for ^{17}F(1st exc) (Table III). For comparison, the single-particle widths for $\ell=0$, 2 decays [throughout this paper (and others) for the orbital angular momentum quantum number of the transferred particle in a direct reaction or the light particle in a resonance reaction, we use lowercase ℓ if that particle is a nucleon (neutron or proton) and capital L for a collection of two or more nucleons (e.g., $2n$, $2p$, α).] to ^{17}F($\frac{1}{2}^-$) are 14.1 keV and 121 eV, respectively. As these spectroscopic factors are certainly less than unity, these decays make at most a minor contribution. [As ^{17}F($\frac{1}{2}^-$) is unbound, these decays would deplete ^{14}O, but not produce ^{17}F.]

To a reasonable approximation, the three lowest $J^\pi=1^-$ $T=1$ states in $A=18$ are linear combinations of three three-particle one-hole ($3p$-$1h$) states, with the hole in $p\frac{1}{2}$ and the three particles being the lowest $J^\pi=\frac{1}{2}^+$, $\frac{3}{2}^+$, $T=\frac{1}{2}$, and $\frac{3}{2}^+$, $T=\frac{3}{2}$. For a fourth 1^-, $3p$-$1h$ state, the $\frac{1}{2}^+$, $T=\frac{3}{2}$ state is not far away, while the next available $J^\pi=\frac{1}{2}^+$ or $\frac{3}{2}^+$ level with $T=\frac{1}{2}$ is about 4 MeV higher (not counting the obvious core-excited $\frac{3}{2}^+$ state at 4 MeV) as is the lowest $p\frac{3}{2}$ hole state. Millener's wave functions [8] for the first four 1^- states of ^{18}O have (in order of increasing E_x) 1.9%, 17.9%, 4.6%, and 8.3%, respectively, of fp particle, the remainder being $3p$-$1h$. All but the lowest have (39–50)% of their wave function containing $(sd)^3$ coupled to $T=3/2$. Pure $3p$-$1h$ configurations, in weak coupling, are expected to have excitation-energy shifts from -20 keV to $+180$ keV, where a minus sign indicates lower energy in ^{18}Ne. States with particles having $T=3/2$ will lie lowest in ^{18}Ne relative to ^{18}O. The lowest $5p$-$3h$ configurations should be almost 50 keV higher in ^{18}Ne than in ^{18}O. Of course, any admixture of $2p\frac{3}{2}$ single particle will cause a downward shift, but the total fp component is small, as listed above, and the $2p\frac{3}{2}$ part of the fp component is small. The small $2p\frac{3}{2}$ admixture is further borne out in the small spectroscopic factors in ^{17}O(d,p) to these negative-parity hole states: $S\lesssim0.03$. For the 7.60, 1^- state in ^{18}Ne the width of 72 ± 20 keV corresponds to a $2p\frac{3}{2}$ S factor of 0.03 ± 0.01. A $2p\frac{3}{2}$ admixture of this magnitude will cause a downward shift of about 50 keV. Thus, any negative-parity states below about 8 or 9 MeV in excitation in ^{18}O will exhibit small absolute values of excitation-energy shift in ^{18}Ne.

The state at 7.71 MeV in ^{18}Ne was not observed in (p,α) and hence was not discussed in Refs. [2,4]. Its absence in that reaction makes it irrelevant for the stellar burning reaction ^{14}O(α,p) and suggests unnatural parity. We agree with Harss *et al.* [1] that it appears to be the analog of ^{18}O(7.771,2^-). Their cross-section data "do not help in the J^π assignment" [1]. They (and we) prefer 2^- on the basis of Coulomb energies as discussed above for the 1^-. This state has proton widths of 59±25 keV and 11±5 keV, respectively, for decay to ^{17}F(g.s.) and first excited state. The sp $\ell=1$ proton widths are 2.6 and 1.7 MeV, giving S values of $(2.3\pm1.0)\times10^{-2}$ and $(6.5\pm2.9)\times10^{-3}$. The ground-state value is well within the limit for the mirror state in ^{18}O. The single-particle $\ell=2$ width for decay of a 2^- in ^{18}Ne to the lowest $\frac{1}{2}^-$ in ^{17}F is 367 eV. Hence, even though the corresponding spectroscopic factor could be large, this decay is also unimportant.

We turn now to the 7.37-MeV state in ^{18}Ne. It obviously has natural parity as it is observed in the (p,α) reaction. For reasons discussed in Ref. [1], the lowest known state in ^{18}O that could be its parent is the 2^+ level at 8.21 MeV, and Harss *et al.* suggest this mirror identification. Such a large shift in excitation energy would require nearly unit $\ell=0$ spectroscopic factor, but the 8.21-MeV state has very little n strength [9–11]. The $d\frac{5}{2}s\frac{1}{2}$ 2^+ strength is used up by the three lowest 2^+ states at 1.98, 3.92, and 5.25 MeV; and the state with dominant $d\frac{3}{2}s\frac{1}{2}$ strength is predicted at 10.9 MeV. The 8.21-MeV level in ^{18}O is almost certainly a core-excited state. Its configuration has been suggested [12] as six-particle four-hole $(6p\text{-}4h)$, along with 4^+ and 6^+ states at 10.29 and 12.53 MeV, respectively, and a 0^+ level remaining to be identified near 7 MeV. Manley *et al.* [13] found that the (e,e') form factor was consistent with a $d\rightarrow d$ transition, but they nevertheless preferred a multiparticle multihole configuration for this state—based primarily [13] on its weakness in (d,p) [14] and (t,p) [15] and its very small neutron width [9]. They state [13] "these observation clearly reveal that the 8.21-MeV state *must* be a multiparticle-multihole configuration ...." They suggest a different $mp\text{-}nh$ configuration from the one we prefer, but primarily on grounds of excitation energy. They state [16] that the evidence for their particular suggested configuration is not strong, but the core-excited nature is. Of course, neither of these core-excited configurations would have much strength in ^{17}O(d,p) because ^{17}O is primarily $1p$ in character, plus a small amount of $3p\text{-}2h$, and the (d,p) reaction transfers only one particle.

No higher ^{18}O states could be the parent of ^{18}Ne(7.37) because then the excitation-energy shift would be even larger. We must conclude, therefore, that ^{18}Ne(7.37) is a natural-parity state whose parent in ^{18}O has yet to be discovered. For reasons outlined below, we suggest $J^\pi=0^+$. In ^{16}O(^{3}He,n) [5], a 7.35-MeV state is observed, though weakly $[\sigma(7.35)\cong0.03\sigma(\text{g.s.})]$, and its angular distribution decreases by a factor of 10 from 0° to 23°. In fact, at 23° the uncertainty overlaps zero. Of the angular distributions displayed in Ref. [5], only that of the 0^+ ground state exhibits such a decrease. The next largest decrease is only about a factor of 2.5. This sharp falloff could be a hint that the 7.35-MeV state might be 0^+. Could a 0^+ level in ^{18}O have eluded identification all these years? Historically, 0^+ states at high excitation have been notoriously difficult to locate. And a 0^+ state is expected somewhere near here from the $6p\text{-}4h$ configuration [12]. In fact, there is a hint of a weak state in both ^{17}O(d,p) [14] and ^{16}O(t,p) [15] just above 7 MeV in excitation energy. In Fig. 1 of Ref. [15], a small

TABLE IV. Properties of ^{18}Ne(7.37) and its possible mirror in ^{18}O.

Quantity	^{18}O	^{18}Ne	
		Expt.[a]	Calculated
E_x (MeV)	(7.02)[b] or (7.03)[c]	7.37±0.06	7.40–7.41[d]
$\sigma/\sigma_{\text{g.s.}}$ (two-nucleon)	≈0.014[b]	≈0.03[e]	
Γ_α (eV)		200±150	
Γ_p (keV)		70±60	(60)[f]
S (nucleon)	(0.12)[c]	0.14±0.12[g]	

[a]Ref. [1], unless otherside noted. α width assumes $\Gamma_\alpha \ll \Gamma p_0$.
[b]From inspection of Fig. 1 of Ref. [15].
[c]Reference [14].
[d]Weak coupling for $6p\text{-}4h$ state.
[e]Reference [5].
[f]Computed assuming $S_\text{n}=S_\text{p}$.
[g]Computed from measured width and our sp width.

bump is visible at 15° between levels 14 and 15 (6.88 and 7.11, respectively). If this is a state in ^{18}O, its excitation energy is 7.02 MeV, and its cross section is 1.4×10^{-2} of that for the g.s. This is close to the ratio of $\sigma(7.35)/\sigma(\text{g.s.})\approx0.03$ in (^{3}He,n) mentioned above. Unfortunately at 7.5° (same figure), the peak is obscured by knock-on protons from a H_2 impurity, so its $L=0$ character cannot be ascertained. In ^{17}O(d,p) [14], the bump has $E_x=7.03$ MeV and is even larger: $\sigma(7.03)\approx0.10\sigma(7.11)$, giving $S_\text{n}=0.12$. For ^{18}Ne(7.37), Γ_p(sp) is calculated to be 500 keV, so that we would expect $\Gamma_p=60$ keV, compared with a total width of 70±60 keV experimentally. Now, what about the Coulomb energy? Hole states generally have higher excitation energies in the proton rich member of the mirror pair, so a shift from 7.02 MeV in ^{18}O to 7.37 MeV in ^{18}Ne has the expected sign. The calculated energy shift for a $6p\text{-}4h$ 0^+ state [^{22}Ne(g.s.)$\times^{12}$C in ^{18}O and ^{22}Mg(g.s.)$\times^{12}$C in ^{18}Ne] is [17]

$$E_x(^{18}\text{Ne},6p-4h)-E_x(^{18}\text{O},6p-4h)$$
$$=M(^{18}\text{O(g.s.)})-M(^{18}\text{Ne(g.s.)})+M(^{22}\text{Mg(g.s.)})$$
$$-M(^{22}\text{Ne(g.s.)})+4c,$$

where c is the Coulomb particle-hole matrix element, known to be near −300 keV, and determined in Ref. [6] to be −288 keV for lower-lying states in ^{18}O-^{18}Ne. The M's are mass excesses [18]. With the known mass excesses, the result is 0.38 MeV, using the Coulomb parameter from Ref. [6]. So the energy shift is reasonable. These results are summarized in Table IV. Of course, it is quite possible that $J^\pi(7.37)=0^+$, but the "bump" at 7.02/7.03 MeV in ^{18}O has another origin. In that case the mirror of ^{18}Ne(7.37) would remain to be identified and we would have no information from mirror symmetry regarding the single-nucleon S factors.

In summary, we present calculations for four states at 7–8 MeV excitation in ^{18}Ne. For the 4^+ at 7.05 MeV, our suggested width is smaller than the accepted value, but within the estimated uncertainty. Using the measured width in ^{18}O and assuming good isospin reduces the uncertainty to about one-third the previous value (Table II). The 1^- and 2^- states at 7.60 and 7.71 MeV, respectively, appear to be as expected.

The 7.37-MeV natural-parity level of ^{18}Ne appears to be the mirror of a previously undiscovered state in ^{18}O, which may be at 7.02 MeV. In both nuclei, these states have some characteristics of a 0^+ level in two-nucleon transfer. Cross sections for (t,p) and $(^3\mathrm{He},n)$ (relative to the g.s.) are similar and S values for single-nucleon transfer agree. If the 0^+ identification is correct, the energy shift is consistent with a $6p$-$4h$ configuration, but not with any other.

For the astrophysical reaction rate arising from the three states discussed here, the newer result of Harss *et al.* is smaller than that of Hahn *et al.* by a factor of about 0.8 at $T_9=1.5$ and a factor of ≈ 0.43 at $T_9=3.0$. In this temperature range, the 4^+ contribution is larger than that of the other two states. For a 4^+ excitation energy of 7.05 MeV, our suggested value of Γ_α leads to a rate that is 56% of the rate of Harss *et al.*, and our uncertainty (if mirror symmetry holds) is 14% compared to 35% in Ref. [1]. Of course, the extra uncertainty arising from uncertainty in resonance energy also produces an uncertainty in rate. For example, if the excitation energy is 7.15 MeV, rather than 7.05, our value of Γ_α increases from 22.6 ± 3.2 eV to 36.2 ± 5.4 eV, producing a larger ω_γ. However, the higher resonance energy produces a smaller population factor—a factor of 0.46 at $T_9=1.5$ and 0.68 at $T_9=3.0$. Even with our reduced uncertainty in ω_γ, the excitation energy should be more reliably determined for a more accurate reaction rate calculation.

The quantities measured in ^{17}F(p,α) for all these resonances are

$$\omega_\gamma(p,\alpha)=[(2J+1)/12]\Gamma p_0\Gamma_\alpha/\Gamma$$

and Γ—the latter usually with a rather large uncertainty. The inelastic proton width to the $1/2^+$ first excited state is Γ_{p_1} and $\Gamma=\Gamma_{\mathrm{p0}}+\Gamma_{\mathrm{p}_1}+\Gamma_\alpha$, with Γ_γ having been neglected. All the α widths quoted here and in Ref. [1] assumed $\Gamma_\alpha \ll \Gamma_{\mathrm{p0}}$ in extracting Γ_α from the two measured quantities. For the 4^+ and 1^- states, Γ_{p_1} was found in Ref. [1] to be negligible, though not for the 2^-. No information regarding Γ_{p_1} is available for the 7.37-MeV state. If it turns out to be a 0^+ state, as we discuss above, the assumption $\Gamma_\alpha \ll \Gamma_{\mathrm{p0}}$ may not hold. Because the α width is then s wave, it could be appreciable, even if the α spectroscopic factor is small. It might even be that Γ_{p_1} is comparable to, or larger than, Γ_{p0}. The (p,p') reaction (Fig. 8 of Ref. [1]) puts an upper limit on the quantity $\Gamma_{\mathrm{p0}}\Gamma_{\mathrm{p}_1}/\Gamma^2$, but close to that upper limit we could have the intriguing possibility of $\Gamma_{\mathrm{p0}}\approx\Gamma_\alpha$, $\Gamma_{\mathrm{p}_1}>\Gamma_{\mathrm{p0}}$. If that were true, then in the reaction ^{14}O(α,p), we could have $\sigma(\alpha,p_1)$ significantly larger than $\sigma(\alpha,p_o)$, and the 7.37-MeV state would then make an appreciable contribution to the relevant reaction rate. Despite the difficulty, a measurement of Γ_{p_1} for this state seems highly desirable.

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