Level structure above the proton threshold of ^{20}Na

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The paper presents an analysis of pairings of mirror states above the proton threshold in ^{20}Na with known states in ^{20}F, including the astrophysically important resonance for the ^{19}Ne(p,γ)^{20}Na reaction. This results in a fully comprehensive matching between the mirror levels in ^{20}Na and ^{20}F in this excitation energy region.

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The structure of ^{20}Na below the proton threshold energy of 2190.1(11) keV [1] is firmly established and the analog partner levels in the mirror nucleus ^{20}F have been identified [2]. The situation is not so clear for the region above the proton threshold. This region has attracted particular interest for some decades because the reaction sequence ^{15}O(α,γ)^{19}Ne(p,γ)^{20}Na is thought to represent the main breakout route between the hot CNO cycles and the rp process in x-ray bursters [3]. The purpose of the present Brief Report is to consider the level structure of ^{20}Na above the proton threshold and its relationship to known levels in ^{20}F [4], shown in Fig. 1.

The most recent study of levels above the proton threshold of ^{20}Na was that of Wallace *et al.* [5] from measurements of the β-delayed proton decay of ^{20}Mg. That paper focused on a search for a weak proton decay branch of the key astrophysical resonance for the ^{19}Ne(p,γ)^{20}Na reaction at ~450 keV. For a detailed discussion of previous studies of the attempt to identify the spin-parity of this resonance, and to determine its strength, readers are referred to Ref. [5] as a starting point. Here we note that it was concluded that the resonance had $J^\pi = 3^+$ and corresponded to a known 3^+ level at 2966 keV in the mirror nucleus ^{20}F [5]. The relatively large Coulomb energy difference has been attributed to a significant percentage of the wave function containing a $2s_{1/2}$ nucleon component [6]. An analysis was presented in Ref. [5] that combined the new high-precision proton threshold energy measurement of Ref. [1] with a precise relative energy difference measurement between this state and a neighboring 1^+ resonance obtained in a high-resolution study of the ^{20}Ne(^{3}He,t)^{20}Na charge exchange reaction [7]. That information was used to derive a new more precise proton resonance energy of 457(3) keV and an excitation energy of 2647(3) keV in ^{20}Na. The following discussion takes the above assignment from Ref. [5] and explores the level structure above this excitation energy in relation to the known mirror level structure in ^{20}F.

Resonances in $p + {}^{19}$Ne scattering studies were identified at precise energies of 797(2) and 887(2) keV with respective 1^+ and 0^+ assignments by Coszach *et al.* [8]. Transitions to both states were seen in the recent β-delayed proton decay study of ^{20}Mg [5]. Using the new proton threshold energy measurement [1] excitation energies of 2987(2) and 3077(2) keV have been derived [5]. These resonances have been paired in shell model studies with states at 3488 (1^+) and 3526 (0^+) keV in ^{20}F, with again the relatively large Coulomb energy differences being associated with large $2s_{1/2}$ components [6,9]. It is important to note that in Table 3 of the β-delayed proton decay study of ^{20}Mg presented by Piechaczek *et al.* [10] an excitation energy of 3001(2) keV is quoted for the 1^+ resonance, which was subsequently reproduced in the compilation of Tilley *et al.* [4]. However, the energy in that table is derived from a 1^+ resonance energy value reported by Coszach *et al.* [11], which was subsequently revised by 20 keV due to an earlier incorrect treatment of the relative energy response of protons and α's in silicon detectors [8].

Also, referring to Table 3 in Ref. [10], a state is given an adopted excitation energy of 2983(7) keV based on a compilation of (^{3}He,t) studies with spin-parity assignment range $>3^-$ or $>4^+$. These values are subsequently quoted in the data compilation of Tilley *et al.* [4]. On close inspection, only the (^{3}He,t) study of Clarke *et al.* [12] gives the (tentatively) quoted spin-parity assignment range. However, in a later paper of Clarke *et al.* [13] explicitly showing comparisons between angular distributions for (^{3}He,t) and (t,^{3}He) data, they propose that the 2986-keV state is paired with the 3488-keV 1^+ state in ^{20}F. In other words, excluding the earlier work of Clarke, which is in contradiction with the later report on their data, there is no evidence for a higher spin state at this excitation energy in the literature. Rather, the data are consistent with only a single 1^+ state at 2987 keV. We note the relatively high value of 3006(10) keV quoted for the early β-delayed proton decay study of Görres *et al.* [14] is 9 keV higher than would be the case if the new proton threshold energy [1] would be used to derive the excitation energy and hence is consistent with this conclusion.

A state is clearly seen around 2858 keV in ^{20}Na in a number of charge exchange reaction studies. In the later study of Clarke *et al.* comparing (^{3}He,t) and (t,^{3}He) reactions a pairing is made with the 2865-keV level in the mirror nucleus ^{20}F [13], which has a tentative 3^- assignment [4]. This pairing and assignment are supported by shell model studies which predict very small, or even negative, Coulomb energy differences for negative-parity 5p-1h states [6,9].

In their high-resolution study of the ^{20}Ne(^{3}He,t)^{20}Na reaction, Smith *et al.* [7] report a level at an excitation energy of 3056(9) keV. A magnetic spectrometer was used in this study, with relative energies between the excited states reported as being measured to an accuracy of +/−2 keV [7]. Hence, using these values relative to the 2987(2) keV state,

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TABLE I. The right-hand side of the table shows the proposed pairing between mirror levels in ^{20}Na and ^{20}F. All footnotes refer to the present excitation energies in ^{20}Na. To the left-hand side of the table excitation energies in ^{20}Na from charge exchange reaction studies are given with references. We note for completeness that the data from Ref. [15] was later reanalyzed by a subset of the original authors assuming only two states in the broad structure at ~3 MeV [22].

(^{3}He,t) [20,21]	(p,n) [21]	(^{3}He,t) [15]	(^{3}He,t) [12]	(^{3}He,t) [7]	Present	^{20}F [4]	Spin parity
2637(15)	2651(20)	2649(16)	2640(20)	2646(9)	2647(3)[a]	2966	3^+
2842(15)	2852(20)	2836(12)	2860(20)	2857(9)	2858(3)[a]	2864	(3^-)
2967(20)		2972(13)	3010(20)	2986(9)	2987(2)[b]	3488	1^+
3046(20)	3053(20)	3035(15)		3056(9)	3057(3)[a]	2968	(4^-)
		3100(14)			3077(2)[b]	3526	0^+
3302(30)			3290(20)		3315(9)[c]	3172	(1^+)

[a]Values determined relative to the 2987(2)-keV [5] state using precise relative energy dispersion values reported in Ref. [7].
[b]Values we obtain here by combining resonance energies from Ref. [8] with the new precise value for the ^{20}Na proton threshold energy [1].
[c]Value taken from the data compilation of Ref. [4].

one can determine a more precise excitation energy value of 3057(3) keV. The energy of this state is not compatible with the 0^+ excitation energy of 3077(2) keV and must represent a different state. Furthermore the upper limit of 16 keV for the intrinsic total width obtained by Smith *et al.* [7] is incompatible with the value of 36(2) keV obtained by Coszach *et al.* for the total width of the 0^+ resonance [8]. In the shell model study of Brown *et al.*, it was initially argued that the known (4^-) state at 2968 keV in ^{20}F "could be the mirror to the 3056 keV state in ^{20}Na" on the basis of the Coulomb energy shifts of negative-parity states [9]. However, that probability was discounted in this same paper [9] because this excitation energy was attributed to the 0^+ resonance due (once again) to the use of the resonance energy value from Ref. [11] rather than from the subsequently published full paper value [8], which is 20 keV higher. We therefore conclude that the 3057(3)-keV level is most likely paired with the (4^-) state at 2968 keV in the mirror nucleus ^{20}F. The states at 3057 and 3077 keV in ^{20}Na would not generally be resolvable in most (^{3}He,t) charge exchange reaction studies. In the high-resolution study of Smith *et al.* it is noted that the peak is broader for the 3056-keV state than for lower lying states [7]. This could be attributable to the intrinsic width of the state; however, close inspection of the spectrum shown in Fig. 2 of that paper is suggestive of a skew shape perhaps compatible with a weakly produced higher lying state. Interestingly, in an early (^{3}He,t) study by Lamm *et al.* [15], three unresolved and unassigned states were reported in this excitation energy region at energies of 2972(13), 3035(15), and 3100(14) keV, respectively, which is consistent with our present conclusions on the energy level structure. It should be noted that for the 1^+ resonance at 2987 keV, the resonance width of 20(2) keV reported by Coszach *et al.* in $p + {}^{19}$Ne scattering [8] is larger than the upper limit of 10 keV set in the earlier high-resolution (^{3}He,t) study of Smith *et al.* [7]. This discrepancy was already noted in Ref. [8].

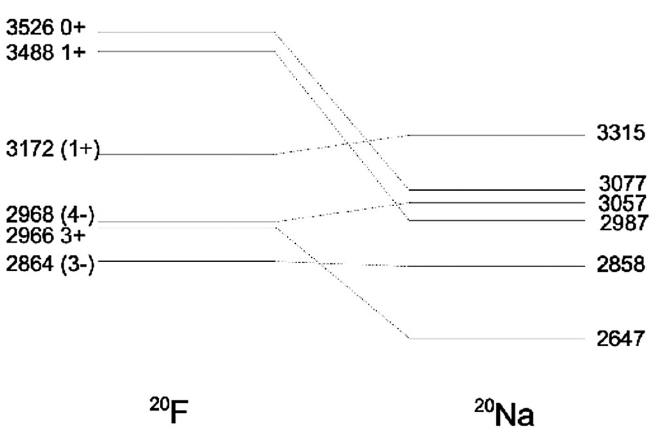

FIG. 1. Energy levels of ^{20}F reported in the data compilation of Tilley *et al.* [4] paired with proposed analog states above the proton threshold energy in ^{20}Na.

Only one level remains unpaired in the mirror ^{20}F in this energy region, assigned as $(0^-, 1^+)$ at 3172 keV [4]. Fortune *et al.* comment that it is most likely a 1^+ state of 6p-2h character [6] based on its production in the ^{18}O(^{3}He,p) reaction [16]. The characterization of this state as not having a predominant $(sd)^4$ configuration is consistent with it not being fed by the β decay of ^{20}O [17] or by neutron capture on ^{19}F [18]. For such states with one or two holes, the excitation energy in the proton-rich partner tends to be higher [19]. In ^{20}Na there is only one remaining further state at 3315(9) keV lying below 3.6 MeV [4]. By process of elimination this state is paired with the 3172-keV state in ^{20}F. This is also consistent with the nonobservation of a β-branch feeding the 3315 keV state from the decay of ^{20}Mg [4,5,10].

The summary of the proposed full pairing of levels above the proton threshold in ^{20}Na with states in ^{20}F is shown in Fig. 1 and Table I. A full matching is achieved with all known ^{20}F levels in this excitation energy region. Nonetheless, in future it would be desirable to confirm these proposed assignments in a high-resolution study. Such a study may enable both the 3057- and 3077-keV levels to be observed in a single experiment, rather than at present being identified separately using (^{3}He,t) and $p + {}^{19}$Ne scattering reaction mechanisms [7,8]. Such a study would also allow the intrinsic widths of these and other levels to be explored, as there remain discrepancies between these two approaches [8].

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