^{22}Mg and the ^{21}Na(p,γ) reaction rate

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We investigate the structure of ^{22}Mg just above the proton threshold using shell-model and Coulomb-energy calculations. Our results disagree with some earlier work in identifying which levels are most important for the ^{21}Na(p,γ) reaction.

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Outbursts of nova are thought to be caused by explosions arising from hydrogen burning of proton-rich unstable nuclei. The detection of γ radiation of such radioactive nuclei offers a method to study the parameters of these nova. The recent stellar observation of the 1.275-MeV γ ray of ^{22}Na suggests its possible origin in such outbursts. The expected reaction sequence is considered to be ^{20}Ne$(p,\gamma)^{21}$Na$(p,\gamma)^{22}$Mg$(\beta^+)^{22}$Na. While the sequence ^{20}Ne$(p,\gamma)^{21}$Na$(\beta^+)^{21}$Ne$(p,\gamma)^{22}$Na is more favorable, the former is more likely to occur at high temperature and density [1]. Therefore, the emphasis in recent investigations has been the resonant structures of ^{22}Mg [2–7]. Of importance are the precise resonant energies and the strengths of proton capture to the levels near threshold. Information concerning the corresponding levels in the better-known nuclei ^{22}Ne and ^{22}Na $(T=1)$ can aid in determining these strengths.

Several reactions have been used to populate states in ^{22}Mg. These include ^{24}Mg(p,t) [4,8], ^{25}Mg(^{3}He,^{6}He) [7], ^{12}C(^{16}O,^{6}He) [5], and ^{21}Na(p,γ) [6]. In the excitation energy region just above the ^{21}Na$+p$ threshold, different reactions appear to populate different states—as is, of course, partially understandable on the basis of reasonable selection rules. Various papers also disagree on some of the J^π assignments and on mirror correspondences between ^{22}Ne and ^{22}Mg. We point to these discrepancies and try to clarify them below.

With a ^{21}Na beam incident on a CH_2 target, Ruiz *et al.* [6] observed three ^{21}Na$+p$ resonances between 6.3 and 6.8 MeV excitation, and gave estimates of their widths. With uncertainties of ±10 keV, their energies are 9, 9, and 33 keV, respectively, higher than those of known states from other reactions that had uncertainties of 6–10 keV. Thus, the lowest two states can probably be identified with the two previously known, but such an identification is less likely for their third state. Ruiz *et al.* conclude these are all $\ell=0$ resonances, and the shape of the first two resonances confirms that conclusion. The third is less obviously s wave. The authors do not state whether their widths are total or elastic widths or, indeed, whether they assumed $\Gamma_{el}=\Gamma_{tot}$ in their analysis. Inspection of their convoluted and unconvoluted curves seems to indicate $\Gamma_{tot}>\Gamma_{el}$ for the upper resonance.

The three resonances in Ref. [6] are far enough above the threshold that $\Gamma_p \gg \Gamma_\gamma$, so that the (p,γ) reaction rate depends primarily on Γ_γ (and J, of course). In the absence of direct measurements of $\omega\gamma$ for (p,γ), the values of Γ_γ from the parent states of ^{22}Ne can be used, *with a suitable model*, to estimate values of Γ_γ in ^{22}Mg. It is probably not sufficient to assume equal γ widths in the mirror nuclei, but most of the relevant positive-parity states in ^{22}Ne are described very well by shell-model calculations within the sd shell. The 0^+ level at 6.90 MeV appears to be the lowest positive-parity state not identified with an obvious sd-shell counterpart. It likely involves excitation of two nucleons into the pf shell, and/or from p to sd. Thus, the shell model should provide a reliable tool for computing the ^{22}Mg γ widths if they are known in ^{22}Ne. Of course, for this procedure to work, the mirror correspondence must be known, and in our view, some of the mirror identifications in the literature [7] are incorrect. We start first with the resonances of Ref. [6], and we then present general results for several states in order to investigate the validity of our procedures.

Our starting point for making mirror identifications between ^{22}Ne and ^{22}Mg is the ^{21}Ne(d,p) reaction [9], which measured ground-state spectroscopic factors for $\ell=0,1,2,3$. States with $\ell=0$ spectroscopic factors should have the largest Thomas-Ehrman (TE) shift. The situation is somewhat complicated because of coupling to the $5/2^+$ first excited state of ^{21}Ne, which lies only 330 keV above the ground state. Several states will have large $\ell=0$ strengths to this excited state, and they are not measurable in (d,p). Thus, we first compare excitation energy shifts with ground-state S_0 values, and then we present calculations of Coulomb energies using the full excited-core coupling amplitudes from a shell-model calculation.

If coupling to excited states was not important, the TE shift should be proportional to the $\ell=0$ spectroscopic factor S_0, so that ratios of ΔE_x divided by S_0 should be relatively constant for different states at about the same excitation en-

TABLE I. States of ^{22}Ne with large $\ell=0$ strength and their probable mirrors in ^{22}Mg.

^{22}Ne E_x (keV)	J^π	$S_0(d,p)$[a]	^{22}Mg E_x (MeV)	$\Delta E_x/S_0$ (keV)
5363	2^+	0.32	5037	1.00
6853	1^+	0.57	6323	1.15
6819	2^+	0.18	6609	0.93

[a]Reference [9].

ergy. From Table I, it is clear that only the 1^+ level at 6853 keV in ^{22}Ne has a large enough value of S_0 to have a Coulomb shift appropriate for the ^{22}Mg level at 6323 keV. With that identification, it then appears that ^{22}Mg (6609) is an excellent choice for the mirror of ^{22}Ne (6819). Even with the large uncertainties in the widths of Ref. [6], this conclusion is also borne out by comparing (Table II) $\Gamma_{calc}=S_0\Gamma_{sp}$ with $\Gamma_{expt.}$.

Now, we turn to a detailed calculation of Coulomb energies for several states, including several for which mirror identifications are clear and several that are still open to question. We first consider positive-parity states and use the $(sd)^6$ shell-model calculations with universal-sd interaction [10]. These shell-model results have displayed agreement with results of ^{21}Ne(d,p) [9] and ^{20}Ne(t,p) [11] reactions.

Ruiz *et al.* suggest identification of ^{22}Ne (6636) with their ^{22}Mg (6332) (6323 in the literature) and ^{22}Ne (6854) with their ^{22}Mg (6813). We disagree with both of these suggestions. First, ^{22}Ne (6636) has no $\ell=0$ strength in (d,p) and hence could not have such a large TE shift. If ^{22}Mg (6813) were the mirror of ^{22}Ne (6854), its width, $\Gamma=S_0\Gamma_{sp}$, would be 117 keV—clearly not possible from the data of Ref. [6]. Additionally, as mentioned earlier, ^{22}Ne (6854) has the appropriate $\ell=0$ strength to be identified with ^{22}Mg (6332). If this latter mirror identification is correct, then we must look elsewhere for the ^{22}Ne state that is the mirror of ^{22}Mg (6780) (their 6813). It thus appears that two of the three mirror identifications suggested by Ref. [6] are incorrect.

Table III contains a list of known states of ^{22}Ne, their J^π, the calculated shell-model energy, and the computed excitation energy shift for ^{22}Mg. For the Coulomb-energy calculation we have used coupling of s and d nucleons to various states of mass 21. For several states of interest we list the spectroscopic factors for coupling to excited states in Tables IV and V. Calculations used a Woods-Saxon well with $r_o=1.25$ fm, $a=0.65$ fm, plus the Coulomb potential of a uniform sphere. Energies are defined by the peak in $d\phi/dE$, where ϕ is the partial wave phase shift. For states with known mirror correspondence, we generally obtain agreement within better than 100 keV; and hence, one would expect to reproduce ^{22}Mg energies within this uncertainty up to the energy of 6.9 MeV in ^{22}Ne, which seems to be the lowest positive-parity intruder state. We now discuss several of these states that are relevant to the ^{21}Na(p,γ) reaction rate.

TABLE II. Energies and widths (keV) of the three ^{21}Na$+p$ resonances of Ref. [6].

E_x	Literature	$\Gamma_{expt.}$	Γ_{sp} $\ell=0$	Γ_{sp} $\ell=2$	$S_0(d,p)$	$\Gamma_{calc}=S_0\ \Gamma_{sp}$
	6323		25			
6332		7^{+4}_{-3}	28	0.40	0.57	16
	6609		104			
6617		14 ± 5	105	2.25	0.18	19
	6780		186			
6813		8 ± 5	205			

^{22}Mg(5714,2_4^+). This is the lowest and most important level of astrophysical significance in ^{22}Mg. Jose *et al.* [2] compared its experimental width of 16.5(4.4) meV, with the radiative width [12] of the ^{22}Ne 6210-keV mirror of 29(9) meV. From the latter, they estimate Γ_γ for the 5714-keV level to be ≈ 23 meV, implying $\Gamma_p \ll \Gamma_\gamma$. Thus, $\omega\gamma \approx 5\Gamma_p/8$. To determine Γ_p, they considered the presumed ^{22}Na* analog level at 5894 keV ($E_x=6545$ keV). The 6.12-MeV state of ^{22}Ne is very weak in (d,p) and has a nonstripping angular distribution. Reference [3] has obtained upper limits on $\ell=0$ and 2 spectroscopic factors in a reanalysis of the data of Ref. [9] for ^{22}Ne (6120). Both theoretical S factors are also very small in the shell-model calculations.

However, in the ^{21}Ne(^{3}He, d) reaction, Garrett *et al.* [13] found S to be ≈ 0.1, much larger than S for the parent ^{22}Ne (6120). This fact rules out ^{22}Na (5894) ($E_x=6545$) as the analog of this state, because that ^{22}Na state has a reasonably large value of S [13]. However, the 6.120-MeV ^{22}Ne level is quite strong in (t,p) [11], and (^{3}He,p) [15,17] populates strongly a state at 6.664 (6.013*) MeV—which, in fact, is suggested to have $T=1$ [14]. We believe it is the analog of ^{22}Ne (6.120). The small S_n values in ^{22}Ne provide small upper limits on Γ_p for the mirror state in ^{22}Mg—which we identify (as have others) at 5.714 MeV. The limits on spectroscopic factors and proton widths are listed in Table VI.

Turning to computed value for Γ_p for this $E_p=212$ keV resonance in ^{22}Mg, Smirnova and Coc [3] used the relation $\Gamma_p=S\Gamma_{sp}$ to get $\Gamma_p(\ell=0)=4.5$ meV. The single-particle width was estimated from scattering phase shifts in a Woods-Saxon well. Bateman *et al.* [4] computed Γ_p using an R-matrix procedure to find 4.6 meV. Our computation (see below and Table VI) yields $\Gamma_{sp}=485$ meV, which with the shell-model value of $S=0.010$ yields $\Gamma_p(\ell=0)=4.8$ meV. [Similar calculations for $\ell=2$ lead to a negligible $\Gamma_p(\ell=2)=0.03$ meV, in good agreement with other estimates.] Using experimental $S's$ from Ref. [3] would give $\Gamma_p(\ell=0)\leq 1.2$ meV and $\Gamma_p(\ell=2)\leq 0.4$ meV. A very recent measurement [16] provides $\omega\gamma=1.03\pm0.16\pm0.14$ meV, consistent with the above estimates and with the expectation $\Gamma_p \ll \Gamma_\gamma$. In Ref. [16], the proton energy is 205.7 rather than 211 keV previously used. With this new energy, our $\ell=0$ single-particle width changes from 485 to 350 meV, providing $\Gamma_p=3.5$ meV using the shell model S, and $\Gamma_p \leq 0.84$ meV using the experimental limit [3] on $S(d,p)$.

^{22}Mg(5837,$3^\pm$). If the 5837-keV state exists in ^{22}Mg (it is reported only in Ref. [17], but may be weakly present in some of the other reactions), it is almost certainly the mirror

TABLE III. ^{22}Mg and ^{22}Ne positive-parity mirror levels (in keV).

shell model				^{22}Ne(expt)				^{22}Mg(calc)	^{22}Mg(expt)	calc-expt
E_x	J^π	$S(\ell=0)$	$S(\ell=2)$	E_x	J^π	$S(\ell=0)$	$S(\ell=2)$	E_x	E_x	ΔE_x
0	0_1^+	0	0.13	0	0_1^+	0	$\leqslant 0.20$	60	0	+60
1368	2_1^+	0.01	1.13	1275	2_1^+	0	0.65	1332	1246	+86
3378	4_1^+		0.53	3358	4_1^+	0	0.05	3331	3308	+23
4455	2_2^+	0.02	0.19	4456	2_2^+	0.05	0.14	4351	4402	−51
5437	1_1^+	0.05	0.60	5329	1_1^+	0.03	0.47	5185	5317	−132
5032	2_3^+	0.24	0.08	5363	2_3^+	0.31	0	5145	5037	+108
5480	4_2^+		0.58	5524	4_2^+	0	0.25	5395	5455	−60
5635	3_1^+		0.17	5641	3_1^1	0	0.07	5377	5294	+83
6179	2_4^+	0.01	0.0011	6120	2_4^+			5805	5714	+91
6344	0_2^+	0	0.05	6235	0_2^+			6023	5965	+58
6396	6_1^+		0.11	6311	6_1^+			6209	6248	−39
6430	4_3^+		0.06	6345	4_3^+			6198	(6250)	−52
6520	3_2^+		0.13	6636	3_2^+	0	0.10	6332	(6248)	+84
6573	2_5^+	0.13	0.02	6819	2_5^+	0.18	0	6507	6609	−102
6663	1_2^+	0.55	0.02	6854	1_2^+	0.55	0	6453	6323	+121

of either the 3^- state at 5910 keV in ^{22}Ne or a 3^+ state. For reasons outlined immediately below, we strongly prefer 3^-.

The 5837-keV level was observed in ^{20}Ne(^{3}He,nγ) by Rolfs *et al.* [17], who suggest it to have $J^\pi=3^-$ with a configuration of $^{23}\mathrm{Mg}\times[p_{1/2}]^{-1}$. Bateman *et al.* [4] assume it is the mirror of the 3^+ 5641-keV level of ^{22}Ne, an identification that would require an unusually large *inverse* TE shift. Of course, a core-excited positive-parity state could have such a shift, but the 5614-keV 3^+ state is almost certainly an sd-shell state. The shell model does remarkably well in accounting for the properties of all the states up to 6.9 MeV in ^{22}Ne, including this 3^+ state. For ^{22}Ne (5641), our calculations (Table III) give an energy for its mirror in ^{22}Mg of 5294 keV. The next 3^+ level in ^{22}Ne is at 6636 keV, much too high to correspond to ^{22}Mg (5837). The (^{3}He,^{6}He) reaction [7] does not see this state, but those authors conjecture that if it exists, it is the mirror of ^{22}Ne (5641, 3^+). We investigated the Coulomb energy for a variety of configurations for a 3^- state. If ^{22}Ne (5910) is $^{21}\mathrm{Ne}(1/2^-)\times d_{5/2}$, the energy of its mirror ^{22}Mg would be 5863 keV. If it is $^{21}\mathrm{Ne(g.s.)}\times f_{7/2}$, the ^{22}Mg energy is 5669 keV. Other 3^- configurations give similar results, as do weak-coupling considerations. We thus support a 3^- assignment for ^{22}Mg (5837). The measured lifetime is <25 ns, $\Gamma_{tot}>24$ meV [12]. The single-particle proton decay width for $\ell=1$ decay to the ^{21}Na ground state is 6.2 eV ($\ell=3$ would be much smaller), but the proton width would be extremely small, as the parent ^{22}Ne (5910) was not observed in ^{21}Ne(d,p) [9]. Even if the 5837-keV level is present in ^{22}Mg, we conclude that is it unlikely to play any role in the ^{21}Na(p,γ) reaction.

^{22}Mg (6323,1^+). The 6853-keV, 1^+, state in ^{22}Ne has the largest $\ell=0$ spectroscopic factor of any of the states observed in ^{21}Ne(d,p). The Coulomb calculations with all the excited-state couplings (Table II) reinforce the large excitation energy shift expected. Thus, these calculations support the identification of ^{22}Mg (6323) as the mirror of ^{22}Ne (6853). As it is the closest to the threshold of the three resonances of Ref. [6], it is the most important of these three for the (p,γ) rate [the most important state for (p,γ) is the 5714-keV state close to the proton-decay threshold discussed above]. If we take the known and calculated γ decays of this state in ^{22}Ne, we can estimate the total γ width of ^{22}Mg (6323) to be 1.39 eV, of which most is $M1$. The adopted lifetime in ^{22}Ne is $340\pm60\times10^{-18}$ s, which corresponds to $\Gamma_\gamma(^{22}\mathrm{Ne})=1.94\pm0.34$ eV. It decays $78\pm7\%$ to the ground

TABLE IV. Spectroscopic factors (from shell-model calculations) for the 3_2^+ and 2_5^+ levels of ^{22}Ne, and the calculated analog and double-analog excitation energies (keV) in ^{22}Na (minus 657 keV) and ^{22}Mg.

J^π	E_x (keV) ^{21}Ne	^{21}Na	ℓ	S	^{22}Na	^{22}Mg
^{22}Ne (6636, 3_2^+)						
$1/2_1^+$	2794	2425	2	0.10	6674	6297
$3/2_1^+$	0	0	2	0.13	6494	6356
$5/2_1^+$	351	332	0	0.17	6434	5937
$5/2_2^+$	3730	3544	2	0.14	6714	6421
$7/2_2^+$	5629	5380	2	0.25	6754	6437
			Average		6625	6301
^{22}Ne (6819, 2_5^+)						
$1/2_1^+$	2794	2425	2	0.08	6857	6380
$3/2_1^+$	0	0	0	0.13	6567	5959
$3/2_3^+$	5549	(5380)	2	0.16	6937	6690
$3/2_4^+$	(6608)	6468	2	0.09	6957	6759
$5/2_1^+$	351	332	0	0.09	6607	6080
			2	0.08	6697	6530
$7/2_3^+$	6174	(5570)	2	0.30	6947	6475
$9/2_4^+$	7360	(7100)	2	0.45	6968	6670
			Average		6877	6507

TABLE V. Spectroscopic factors (from shell-model calculations) for the 1_2^+ and 3_3^+ levels of ^{22}Ne, and the calculated analog and double-analog excitation energies (keV) in ^{22}Na (minus 657 keV) and ^{22}Mg.

J^π	E_x (keV) ^{21}Ne	^{21}Na	ℓ	S	^{22}Na	^{22}Mg
^{22}Ne (6854, 1_2^+)						
$3/2_1^+$	0	0	0	0.55	6592	6028
$3/2_2^+$	4685	4468	2	0.22	6952	6627
$3/2_3^+$	5549	(5380)	2	0.30	6972	6715
$5/2_3^+$	4525	4294	2	0.43	6945	6599
$7/2_1^+$	1746	1716	2	0.12	6833	6685
$7/2_2^+$	5629	5380	2	0.05	6972	6635
$7/2_5^+$	(7653)	(7300)	2	0.10	7012	6611
			Average		6838	6453
^{22}Ne (7340, 3_3^+)						
$1/2_1^+$	2794	2425	2	0.08	7348	7077
$1/2_2^+$	5690	5459	2	0.06	7448	7139
$3/2_1^+$	0	0	2	0.15	7148	6930
$3/2_2^+$	4685	4418	2	0.12	7420	7063
$5/2_1^+$	351	332	0	0.11	7060	6441
			2	0.09	7418	6971
$5/2_3^+$	4525	4294	2	0.21	7188	7099
$7/2_1^+$	1746	1716	2	0.12	7198	6750
$7/2_2^+$	5629	5380	2	0.08	7448	7121
$7/2_3^+$	(6174)	(5770)	2	0.10	7458	7046
$9/2_3^+$	(6448)	(6200)	2	0.08	7468	7152
			Average		7318	6972

state and 22±7% to the 2_1^+ state. This state has one of the largest γ widths of any state in this region. That fact, plus its nearness to threshold, should cause it to dominate.

^{22}Mg (6609, 2^+). As discussed above, this state (6609 in the literature, 6617 in Ref. [6]) is almost certainly the mirror of ^{22}Ne (6819). Its Coulomb-energy calculation (Table IV) supports this view. If we take the $\ell=0$ spectroscopic factor of 0.18 from (d,p) [9] and our calculated single-particle width in ^{22}Mg, we get a calculated proton width of 19 keV, to be compared with 14±5 keV measured in Ref. [6]. In the (^{3}He,^{6}He) reaction [7], this state seems to exhibit a natural width—estimated by us to be about 11 keV, after correcting for experimental resolution of 5–6 keV.

^{22}Mg (6813). As mentioned above, this may or may not be the state at 6780 keV in the literature. The energy of 6813 keV is from Ref. [6], who estimate a width of 8±5 keV. Of the three resonances of Ref. [6], this one looks least like $\ell=0$ and may have $\Gamma_{tot}>\Gamma_{el}$. One possibility is that some of the width comes from $\ell=0$ decay to the $5/2^+$ state of ^{21}Na, after being formed via $\ell=2$. Table V presents Coulomb-energy calculations for the 7340-keV state of ^{22}Ne, identified with the 3_3^+ shell-model state. We note that the $\ell=0$ spectroscopic factor for decay to $5/2_1^+$ is 0.11. We calculate the single-particle width for this excited-state decay to be 58 keV, giving $\Gamma^*=S\Gamma_{sp}=6.4$ keV. If ^{22}Ne (7340) is 3^+, its (d,p) spectroscopic factor [9] is 0.05, which when combined with the $\ell=2$ ground-state single-particle width of 6.4 keV, gives $\Gamma_{el}=0.32$ keV in ^{22}Mg, significantly less than the excited-state width.

TABLE VI. Properties of the 6120-keV level of ^{22}Ne and its probable mirror at 5714 keV in ^{22}Mg.

^{21}Ne(d,p)	expt[a]	$S_0\leqslant 0.0024$ $S_2\leqslant 0.014$
	Shell model	$S(\ell=0)=0.010$ $S(\ell=2)=0.0011$
^{22}Mg[b]	E_x(calc) = 5805 keV E_x(expt) = 5714 keV $\Gamma_{sp}(\ell=0)=485$ meV $\Gamma_{sp}(\ell=2)=28$ meV $\Gamma_p(\ell=0)=4.8$ meV (shell model), $\leqslant 1.16$ meV (expt) $\Gamma_p(\ell=2)=0.03$ meV (shell model), $\leqslant 0.39$ meV (expt)	

[a]Reference [3], reanalysis of data in Ref. [9].
[b]We identify ^{22}Na($E_x=6664$ keV) ($E^*=6013$ keV) as the third member of this isospin triplet. Our computed energy is $E^*=6059$ keV in ^{22}Na.

^{22}Mg other states. The 4^+ and 6^+ states at 6311 and 6345 keV, respectively, in ^{22}Ne probably correspond to the doublet of states at 6248 keV in ^{22}Mg. Their high spin makes them irrelevant for the (p,γ) reaction. The 0^+ level at 6235 MeV in ^{22}Ne is probably either the 5962- or 6046-keV state in ^{22}Mg, the other being 1^-. Reference [8] has assigned 0^+ to 6046 and a tentative 1^- to 5962, as the mirror of ^{22}Ne (6691). They also find 5714 to be consistent with 2^+, in agreement with its identification (discussed earlier) with ^{22}Ne (6120). The only other state which remains to be identified in this region is the mirror of ^{22}Ne (6636, 2^+ or 3^+). We identify it as the shell-model 3_2^+ state and our computed ^{22}Mg energy is 6301 keV. It may be unresolved from either the 4^+, 6^+ doublet or the 6323-keV 1^+ state. However, the absence of $\ell=0$ makes this state and the 0^+ and 1^- above irrelevant for the (p,γ) reaction.

In summary, we have used shell-model calculations and computations of Coulomb energies for states in ^{22}Ne and their mirrors in ^{22}Mg. It appears that two of the mirror correspondences suggested in Ref. [6] are incorrect. We suggest that the 1^+ state at 6323 keV will dominate the (p,γ) reaction rate, and that the 6813-keV state may have a significant proton-decay branch to the first excited state of ^{21}Na.

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