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H Terry Fortune
University of Pennsylvania, fortune@physics.upenn.edu

Rubby Sherr
Princeton University

B A. Brown
Michigan State University

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Lowest 2^+, $T = 2$ states in ^{20}Mg and ^{20}F

H. T. Fortune*
Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

R. Sherr
Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

B. A. Brown
Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA

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A recent experiment located the lowest 2^+ state in ^{20}Mg and discovered that the corresponding 2^+, $T = 2$ state in ^{20}F does not fit expectations of the isobaric multiplet mass equation without a d term. We have calculated the energies of the ground and 2^+ states in ^{20}Mg and the 2^+ in ^{20}F in a potential model, using shell-model spectroscopic factors. We conclude that this important ^{20}F state has likely never been observed, and suggest a reaction to find it.

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The $A = 20$ isospin quintet of nuclei has the distinction of being the lightest quintet that is wholly within the sd shell. As such, it is an important testing ground for investigating refinements to the shell model, including the calculation of Coulomb energies, possible breaking of isospin symmetry, etc. In ^{20}O some core-excited states are present, but results of the ^{18}O(t,p) reaction [1] demonstrated that the ground state (g.s.) and first-excited 2^+ state are very well described totally as $(sd)^4$ states. This conclusion was supported for the g.s. by a calculation [2] of the mass of ^{20}Mg(g.s.) and by a fit [3] of the $A = 20$, $T = 2$ g.s. masses to the quadratic isobaric multiplet mass equation (IMME). However, a problem arose for the 2^+ states.

A calculation [2] of the mass of the ground state (g.s.) of ^{20}Mg missed the known value [4] by only calc–exp $= -21(27)$ keV, even though this calculation was quite simple. It included only the g.s. of ^{19}O (and ^{19}Na) coupled to a $1d_{5/2}$ nucleon. (Throughout the paper, whenever we quote an experimental energy and its uncertainty, the energy and uncertainty are both from the cited reference. We believe these are all 1σ uncertainties, unless stated otherwise. We have not attached an uncertainty to the calculated energies, but the reliability of the calculations is addressed along the way.) The same calculation missed the energy of ^{20}F$(0^+, T = 2)$ by $+41(3)$ keV. Using the quadratic IMME, a best fit [3] missed the ^{20}Mg(g.s.) mass by $-18(27)$ keV, but got the lowest 0^+, $T = 2$ state of ^{20}F approximately correctly with a resulting χ^2 of 0.69. Those workers [3] were the first to observe the 2^+ in ^{20}Mg and measure its excitation energy as 1.598(10) MeV. Fitting the 2^+ in three of the nuclei (^{20}O, ^{20}Ne, and ^{20}Mg) (an exact fit) missed the 2^+ energy in ^{20}F [5] by calc–exp $=$ 161(100) keV. Including all four known energies (the state is not known in ^{20}Na) with the addition of a cubic term gave a d coefficient of 55(33) keV, quite a large value. This discrepancy prompted us to revisit our earlier calculation and to include the 2^+ states in ^{20}F and ^{20}Mg.

The present calculation uses spectroscopic factors for ^{20}O$\rightarrow^{19}$O from a full $(sd)^4$ shell-model (sm) calculation, with the USD interaction [6]. However, as we shall see below, it turns out that a severely truncated calculation (using only the three lowest states of ^{19}O) works very well.

A standard shell-model calculation contains no Coulomb interaction. Thus, if the isospin is not zero, the sm calculation provides relative energies for states of the nucleus with $T_z = T$. Here T is isospin and $T_z = (N–Z)/2$, where N and Z are neutron and proton number, respectively. If energies in the $T_z \neq T$ nuclei are desired, then the Coulomb interaction must be inserted. Attempts have been made [7] to include it directly in the sm calculations by modifying the nucleon-nucleon interaction (single-particle energies and two-body residual interaction matrix elements). They usually falter on questions of energy, orbital, and A dependence, on the question of how much isospin nonconservation to include, and the relative importance of one- and two-body (and possibly three-body) terms. Another difficulty is with the radial wave functions. The potential-model wave functions have the correct asymptotic behavior (tail determined by binding energy), but the sm ones do not (because they are eigenfunctions of a harmonic oscillator). One sm + Coulomb approach [8] has been applied to ^{20}Mg.

Our approach is different and relies on the completeness of a one-nucleon expansion in basic quantum mechanics. For any state in nucleus A, its wave function can be written as a sum of terms, each of which is the product of an expansion coefficient, the wave function of a state in nucleus A-1, and a nucleon wave function of relative motion:

$$\Psi_i(A, J_i) = \Sigma a_{ik} \Phi_k(A-1, J_k) u_j(n),$$

where total angular momentum J_i is the vector sum of J_k and j (the latter being 1/2, 3/2, and 5/2 in the sd shell). The sum is over all terms consistent with angular-momentum coupling.

*fortune@dept.physics.upenn.edu

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TABLE I. Spectroscopic factors for ^{20}O(g.s.)→^{19}O. (Energies are in MeV.)

$2J$ (^{19}O)	n	S	E_x (^{19}O)	E_p (^{19}Na)
1	1	0.3217	1.47	1.066
	2	0.0134		
	3	0.0003		
	4	0.0011		
	5	0.0001		
	Sum	0.3366		
3	1	0.0687	0.096	0.44
	2	0.0009		
	3	0.1118	(5.54)	(5.67)
	4	0.0172		
	5	0.0006		
	Sum	0.1992		
5	1	3.4014	0.00	0.32
	2	0.0045		
	3	0.0141		
	4	0.0009		
	5	0.0246		
	6	0.0137		
	Sum	3.4592		
	Total	3.995		

A sm calculation provides numerical values for the expansion coefficients, which are in one-to-one correspondence with the spectroscopic factors. This procedure is exact, but it is convenient only when the total number of important core states is small. (For this reason we frequently check to see if a truncated basis might work.) In the present case of $A = 20$, $T = 2$, the total number is manageable, but (as we shall see) a rather severe truncation works extremely well.

In our procedure, we assume that the expansion coefficients are equal for a given state and its analog, and that the effects of the Coulomb interaction are limited to changes in the radial wave function. We did not invent this technique, but we have frequently used it to compute mass excesses of proton-rich nuclei and/or energies of excited states in those nuclei, including ^{8}C [9], ^{9}B [10,11], ^{10}C [11], ^{11}N [12], ^{12}O [13,14], ^{14}F [15], ^{15}F [16–18], ^{16}Ne [9], ^{17}Ne [19,20], ^{18}Ne [21–23], ^{18}Na [20,24], ^{19}Ne [25], ^{19}Mg [26,27], ^{20}Na [28], ^{20}Mg [2], ^{22}Mg [29], ^{17}Na [30], and ^{40}Sc [31]. Perhaps the most striking example of the success of this approach was the prediction [26] of the g.s. energy of ^{19}Mg: $E_{2p} = 0.87(7)$ MeV. We assigned an uncertainty of 70 keV to those calculations, because the energies of the relevant core states in ^{18}Na were not known, and it was necessary to also compute them. A later experiment [32] found $E_{2p} = 0.75(5)$ MeV, just at the limit of our uncertainty.

Our procedure employs a Woods-Saxon nuclear potential for the calculation of a single-particle (sp) wave function. Geometric parameters are $r_0 = 1.26$ fm, $a = 0.60$ fm. For each term in the one-nucleon expansion of the total wave function mentioned above, we vary the potential well depth to fit the known energy of the state. We then use this potential plus the Coulomb potential of a uniformly charged sphere to calculate the energy of the core+proton sp state. After this has been done for all the components being included, we weight these energies with the relevant spectroscopic factors to obtain our predicted energy for the analog state. In the present case, the first step involves $^{19}\mathrm{O} + n$, the second has $^{19}\mathrm{Na} + p$. As for ^{19}Mg, some of the needed core-state energies in ^{19}Na are not known [33], and we had to calculate them. However (unlike ^{19}Mg), it will turn out that their contributions are small.

An alternative method might be to use the neutron radial wave function to compute the expectation value of the Coulomb interaction. That is not our procedure. We solve the one-nucleon Schrödinger equation twice—once for a neutron, then for a proton, using the same nuclear potential. The first calculation provides the well depth that reproduces the neutron binding energy. The second one gives the proton energy for that well depth.

We start with the ground state, for which the spectroscopic factors are listed in Table I. To compute the energy of the g.s. of ^{20}Mg we first calculate the g.s. of ^{20}O for its various $^{19}\mathrm{O} + n$ components, using a Woods-Saxon potential well having $r_0 = 1.26$ fm, $a = 0.60$ fm. For each component, the well depth is varied to fit the known n binding energy. Then this potential, plus the Coulomb potential of a uniformly charged sphere with $r_{0c} = 1.40$ fm, is used to compute the energy of ^{20}Mg as $^{19}\mathrm{Na}+p$.

For the individual configurations, the results depend primarily on the neutron binding energy for the relevant core, and on whether the neutron is s or d, with s states coming lower in the proton-rich member of a mirror pair. This effect is well known, and is sometimes called the Thomas-Ehrman

TABLE II. Spectroscopic factors for ^{20}O(2^+)→^{19}O. (Energies are in MeV.)

$2J$ (^{19}O)	n	$2s_{1/2}$	$1d_{3/2}$	$1d_{5/2}$	E_x (^{19}O)	E_p (^{19}Na)
1	1	–	0.0189	0.1005	1.47	1.066
	2	–	0.0067	0.0259		
3	1	0.0345	0.0141	1.4304	0.096	0.44
	2	0.0779	0.0043	0.0258	3.067	(3.09)
5	1	0.1491	0.0420	0.7176	0	0.32
	2	0.0304	0.0002	0.0114	3.154	(2.78)
7	1	–	0.0186	0.1277	2.779	(2.785)
9	1	–	–	1.0084	2.372	(2.606)
	2	–	–	0.0283		
	Sum	0.2919	0.1048	3.4760		

TABLE III. Calculated and experimental $2p$ energies (MeV) in ^{20}Mg.

	Core states	g.s.	2^+	E_x (2^+)	Reference
Calculated	All	–2.341	–0.749	1.592	Present work
	First three	–2.339	–0.736	1.603	Present work
Experimental		–2.325(27)		1.598(10)	Ref. [3]

effect. For the g.s., the difference is larger because to make a 0^+ state with an $s_{1/2}$ nucleon requires the core state to also have $J^\pi = 1/2^+$. Additionally the excitation energy of the $1/2^+$ state in ^{19}Na [34] is about 0.7 MeV lower than in ^{19}O. In fact, we find here that most of the effect comes from the core energy, not from the energy of the last neutron, because, in the present case, the binding energies are large—$E_n = -9.077$ MeV for ^{20}O(g.s.) = ^{19}O(1.472, $1/2^+$) + n. However, the overall effect for the g.s. is much smaller than the single-particle value, because (as can be seen in Table I) the $s_{1/2}$ content of ^{20}O(g.s.) is less than 10% of the total strength.

For each configuration of $^{19}\mathrm{O} + n \rightarrow {}^{19}\mathrm{Na} + p$, we weight the calculated energy by the relevant spectroscopic factor. We need the energy in ^{19}Na of the second $5/2^+$ and third $3/2^+$ states. Reference [35] observed the second $3/2^+$ and $5/2^+$ states as resonances in $^{18}\mathrm{Ne} + p$, at $E_p = 2.78$ and 3.09 MeV, but could not determine which was which. We assume the lower is $5/2^+$. The third $3/2^+$ $(sd)^3$ state of ^{19}O occurs in a region in which $3/2^+$ core-excited states are also present. We take as $(sd)^3$ the one with a large $d_{3/2}$ spectroscopic factor—$E_x = 5.54$ MeV. We estimate its energy in ^{19}Na to be $E_p = 5.67$ MeV ($E_x = 5.35$ MeV). The g.s. calculation does not depend very much on this value. A shift of 300 keV in its energy in ^{19}Na causes only a 7-keV shift in ^{20}Mg(g.s.). Using all the ^{19}O states for which the spectroscopic factor is larger than 0.02, the prediction for ^{20}Mg(g.s.) is $E_{2p} = -2.341$ MeV. This is the total energy for $^{20}\mathrm{Mg} = {}^{18}\mathrm{Ne} + 2p$. Because ^{19}Na(g.s.) is unbound by 0.32 MeV [8], the $1p$ energy is then -2.66 MeV. Repeating the calculation with only the three lowest states, with $J^\pi = 5/2^+, 3/2^+$, and $1/2^+$, the result is $E_{2p} = -2.339$ MeV—only a 2-keV difference. The experimental value [36] is $-2.325(27)$ MeV. So, in the full calculation we have calc–exp = $-16(27)$ keV. Recall that for only one component [^{19}O(g.s.) + $d_{5/2}$], the result [2] was calc–exp = $-21(27)$ keV. With satisfactory agreement for the g.s., we now turn to the 2^+ state of ^{20}Mg.

For the 2^+ calculations, we have again used all the components with spectroscopic factors larger than 0.02. These are listed in Table II. Note that for core states with $J^\pi = 3/2^+$ or $5/2^+$, both $\ell = 0$ and 2 are allowed. Also, as for the g.s., we have performed a truncated calculation using only the lowest three states for $A = 19$. For the full calculation for the 2^+ state we need the excitation energies of the second $3/2^+$ and $5/2^+$ states of ^{19}Na, as well as the first $7/2^+$ and $9/2^+$. For the first two, we take the energies mentioned above for the resonances in $^{18}\mathrm{Ne} + p$. The results are insensitive to this choice. Interchanging them produces only a 4-keV shift in the predicted 2^+ energy. For $7/2^+$ and $9/2^+$, we have computed their energies in ^{19}Na, using spectroscopic factors from a simplified $(sd)^3$ sm calculation, in the spirit of Lawson [37], with $s_{1/2}$ and $d_{5/2}$ only. Results are $E_p = 2.61$ and 2.78 MeV for $J^\pi = 9/2^+$ and $7/2^+$, respectively.

Again, results for the full and truncated computations are similar (Table III). The full calculation gives $E_{2p} = -0.749$ MeV, and the truncated one $E_{2p} = -0.736$ MeV. These correspond to 2^+ excitation energies in ^{20}Mg of 1.592 and 1.603 MeV, respectively, to be compared with the experimental value [3] of 1.598(10) MeV. Therefore, we miss the excitation energy by -6 or $+5$ keV, less than the experimental uncertainty. This result provides some confidence that we should be able to make a reliable estimate of the 2^+, $T = 2$ energy in ^{20}F.

In ^{20}F, the $T = 2$ states are composed of (3/4) ($^{19}\mathrm{F}^* + n$) and (1/4) ($^{19}\mathrm{O} + p$), so we compute the two separately and weight with these factors. The lowest $5/2^+$, $3/2^+$, and $1/2^+$, $T = 3/2$ states in ^{19}F [33] are at excitation energies of 7.540(1), 7.661(1), and 8.793(2) MeV, respectively. We note that the uncertainties in these energies are small enough that they will not contribute significantly to any uncertainty in the ^{20}F calculation. In this case, the higher-lying $T = 3/2$ states in ^{19}F are not known, so we can do only the truncated calculation, but we include both $\ell = 0$ and 2 for the $3/2^+$ and $5/2^+$ cores of the 2^+ state. The result is a predicted excitation energy of 8.194 MeV for the lowest 2^+, $T = 2$ state of ^{20}F (Table IV). Because the truncated ^{20}Mg calculation missed the 2^+ excitation energy by only 5 keV, we expect it to be as reliable in ^{20}F. (The proton configuration contributes only 25% here.)

The prediction [3] of the IMME without a d term was $E_x = 8.211$ MeV. The experimental excitation energy [5,38] of the supposed 2^+, $T = 2$ state is 8.05(10) MeV. Our value is 17 keV closer to the experimental energy, but still misses it by 144(100) keV. We expect that a new measurement of this excitation energy will produce a different number. In a core+single-particle picture, the 2^+–0^+ energy difference is smaller in ^{20}Mg than in ^{20}O because the 2^+ state has a larger $s_{1/2}$ parentage and because the 2^+ state is less bound. But, with the compiled energies in ^{20}F, the 2^+–0^+ splitting is less than in ^{20}Mg, an unlikely scenario.

It is possible that isospin mixing plays a role here, and shifts the energy somewhat. The density of 2^+, $T = 1$ states in the vicinity of the 2^+, $T = 2$ state is undoubtedly quite high, especially considering the large number of core-excited

TABLE IV. Excitation energies (MeV) of lowest 2^+, $T = 2$ state in ^{20}F.

Source	Result	Reference
Coulomb energy	8.194	Present work
IMME	8.211	Ref. [3]
Experimental	8.05(10)	Refs. [5,38]

configurations that can exist in this region [39]. The predicted 2^+ energy is unbound to neutron decay by about 1.6 MeV, but in the absence of isospin mixing that decay is isospin forbidden. If T mixing is present, then the decay from the $T = 1$ component would be expected. A state at 8.15 MeV has been seen [5] with a width of 180 keV in (n,γ) and 209 keV in (n,n). If this is the g.s. width, it would correspond to $\ell = 2$, for which the isospin-allowed single-particle width is about 440 keV.

The master list in the compilation [5] for ^{20}F lists states at 8.113(4), 8.147(6), and 8.268(12) MeV, with widths of 195, 15 keV, and unknown, respectively. But all three of these states were observed [40] in the ^{14}N(^{7}Li,p) reaction—which should not populate a $T = 2$ state. Of course, if the isospin is mixed, they could be populated. The first of these may be the same state as the one mentioned above that was observed as a neutron resonance, but its width is far too large for a predominantly $T = 2$ state.

It is possible that the supposed 2^+, $T = 2$ state has been misidentified. The only reaction to populate it is ^{22}Ne(p,^{3}He) [38]. Inspection of spectra for this reaction and for ^{22}Ne(p,t) reveals that the 0^+, $T = 2$ state is strong and sharp in both, but the supposed 2^+, $T = 2$ peak is weak and poorly defined. Also, nothing prohibits the formation of $T = 1$ states in these reactions. Perhaps the ^{22}Ne(p,^{3}He) experiment should be repeated. It is possible that this important state has never been observed. Or, given the strength of ^{20}O(2^+) in the ^{18}O(t,p) reaction [1], it might be easier to identify the 2^+, $T = 2$ state of ^{20}F with the ^{18}O(^{3}He,p) reaction. Earlier investigations [41,42] of this reaction did not reach this high in excitation.

To summarize: We find that the earlier disagreement of the ^{20}F 2^+, $T = 2$ state with the IMME is true also for our potential-model calculations. This state may never have been observed. The reaction ^{18}O(^{3}He,p) probably offers the best method to find it.

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