PHYSICAL REVIEW C VOLUME 58, NUMBER 6 DECEMBER 1998

Coulomb energies in ^{18}Ne

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(Received 17 August 1998)

We compute Coulomb energies for positive-parity levels in the mirror nuclei ^{18}O and ^{18}Ne. The dependence on the configuration and binding energy is explicitly taken into account, using wave functions containing two-particle– and four-particle–two-hole components. Predictions are made for 2_3^+, 3_1^+, and 4_2^+ states. [S0556-2813(98)01612-4]

PACS number(s): 21.10.Sf, 27.20.+n, 21.60.Cs, 21.60.Ev

I. INTRODUCTION

Coulomb energies of the positive-parity levels of ^{18}Ne, mirrors of those of ^{18}O, vary considerably from level to level as is generally the case, reflecting the variation of configurations and the configuration and binding-energy dependence of Coulomb energies. If the positive-parity levels are describable in terms of the spherical shell model, a potential model such as that used in Ref. [1] has some success. Here one uses the single-particle $\frac{5}{2}^+$, $\frac{1}{2}^+$, and $\frac{3}{2}^+$ levels of ^{17}O and ^{17}F, coupling $1d$ or $2s$ nucleons to them. Reasonable results are obtained for a few levels but others are poorly reproduced. There is considerable evidence that the positive-parity levels of ^{18}O cannot be adequately described as two $(1d,2s)$ neutrons coupled to an inert core. Shell-model calculations [2], for example, predict the third 2^+ level to be near 9.5 MeV whereas the experimental 2_3^+ level is near 5.1 MeV; similarly the 0_3^+ is at 5.33 MeV rather than at the calculated value of $\sim$14 MeV.

Many publications have considered the inclusion of deformed particle-hole [four-particle–two-hole (4p-2h)] components. Nero, Adelberger, and Dietrich [3] have reviewed some of these efforts and then carried out an elaborate calculation of two-particle Coulomb energy shifts with the wave functions of Benson and Flowers [4].

We have computed the Coulomb energies for the collective particle-hole components using the method of Sherr and Bertsch [5] assuming the structure to be $[{}^{20}\mathrm{Ne}(J^\pi)\otimes{}^{14}\mathrm{C}_g$ or $^{14}\mathrm{O}_g]$. The shifts for the shell-model two-particle components were computed with a Woods-Saxon well with $r_0=1.25f$ and $a=0.65f$ assuming $2s$ or $1d$ nucleons coupled to the single-particle $\frac{5}{2}^+$, $\frac{1}{2}^+$, and $\frac{3}{2}^+$ levels of ^{17}O and ^{17}F. The Coulomb potential was that of a uniform sphere of radius $r_0A^{1/3}$.

The wave functions of Lawson, Serduke, and Fortune (LSF) [6]—consisting of $(1d,2s)$ two particle components and a 4p-2h collective amplitude—were used. These are listed in Table I and are the ''Constrained II'' sets of their Tables III, IV, and V.

II. RESULTS

The shift of the 4p-2h component of level J^+ in ^{18}Ne relative to its value in the ^{18}O mirror is given by [5]

$$^{18}\mathrm{Ne}(J^+) - {}^{18}\mathrm{O}(J^+) = {}^{14}\mathrm{O}(gnd) - {}^{14}\mathrm{C}(gnd) + 4c,$$

where c is the Coulomb energy of a $p_{1/2}$ proton and $(2s,1d)$ proton. In Ref. [5], the value of c was taken to be 355 keV for a best fit to n-particle–one-hole levels but this yields shifts 103–262 keV too high for 0^+ states. We therefore choose a value of c which best reproduces the experimental values for the most highly collective levels, namely, 0_2^+ and 2_3^+ of Table I. This value of c is 288 (12) keV. With the ^{14}O-^{14}C mass excess difference of 4987 keV the shift in mass excess of the collective components from ^{18}O to ^{18}Ne is 6139(48). The shift in excitation energy is this minus the ground state difference of 6101 keV or +38(48) keV. This shift for the collective component is the same for all the levels of Table I as the spin of the 4p-2h component is that of ^{20}Ne which is constant for both mirrors. [Thus for the collective components $E_x({}^{18}\mathrm{Ne})=E_x({}^{18}\mathrm{O})+38(48)$ keV.]

Our final results are listed in Table II. The experimental data are from Tilley *et al.* [7]. For the 2_3^+ level of ^{18}Ne, they list two possible levels, both of which we include. In the fifth column we list our (calculated minus experimental) values with uncertainties due to the assumed uncertainty in c. The differences found in Ref. [3] are shown in column 6. Except

TABLE I. Components from ''constrained II'' wave functions from LSF. [a]

	$(d_{5/2})^2$	$(s_{1/2})^2$	Coll	
0_1^+	0.719	0.192	0.088	
0_2^+	0.213	0.112	0.676	
0_3^+	0.068	0.696	0.236	
	$(d_{5/2})^2$	$(d_{5/2},s_{1/2})$	Coll	Other [b]
2_1^+	0.599	0.235	0.120	0.046
2_2^+	0.381	0.366	0.251	0.002
2_3^+	0.002	0.362	0.629	0.007
	$(d_{5/2})^2$	$(d_{5/2},d_{3/2})$	Coll	
4_1^+	0.972	0.023	0.004	
4_2^+	0.014	0.154	0.832	

[a] Reference [6].

[b] Minor components were included in all final calculations.

0556-2813/98/58(6)/3292(3)/$15.00

TABLE II. Mirror states ^{18}O and ^{18}Ne.

J^π_n	$E_x(^{18}\mathrm{O})$	$E_x(^{18}\mathrm{Ne})$		$E_x(^{18}\mathrm{Ne})$		$\Delta E_c(^{18}\mathrm{Ne}-{}^{18}\mathrm{O})$
	Expt. [a]	Expt. [a]	Calc.	Calc.-Expt.		Expt. [a]
				Present results	Ref. [3]	
0^+_1	0	0	-44	$-44(4)$	$+140$	7663
2^+_1	1982	1887	1877	$-10(6)$	$+24$	7568
4^+_1	3555	3376	3419	$+43(1)$	-50	7484
0^+_2	3634	3576	3553	$-23(32)$	-28	7605
2^+_2	3920	3616	3574	$-42(12)$	-41	7359
2^+_3	5255	5090	5022	$-68(30)$	-35	7498
2^+_3	5255	5146	5022	$-124(30)$	-91	7554
0^+_3	5336	4590	4619	$+29(11)$	-40	6917
4^+_2	7.117	(7.05) [b]	7.086	$+(40)(40)$		
3^+	5378	(4.56) [c]	4642			

[a] Reference [7].

[b] Reference [8].

[c] Reference [9].

for 0^+_1 and 2^+_3 levels, the results of the two calculations are equally reasonable, with deviations of less than 1% of the Coulomb shifts in column 7.

Our results for the two possible 2^+_3 levels at 5090 and 5146 keV suggest that the lower level is the correct one. This supports the conclusion of Hahn *et al.* [8] that the experimental widths of these two states show that the 5090 keV level is the 2^+ state. Its experimental width is 45 ± 5 keV, and that of the 5146 keV level is 515 keV. Their conclusion is supported by our following calculation. Using the wave function of the 2^+_3 state in Table I and our computed value of 270 keV for $\Gamma_{\mathrm{s.p.}}$, we find $\Gamma(2s)=98$ keV, in reasonable agreement with experiment. We agree with their conclusion that the 2^+_3 state is not available as a resonance in the astrophysically interesting ($^{14}\mathrm{O}+\alpha$) reaction whose threshold is 5110 keV.

In Ref. [7], the second 4^+ level of ^{18}Ne is tentatively identified at 6.297 MeV. Hahn *et al.* [8] conclude that this level and its close neighbors at 6.5 and 6.353 MeV are rather the analogs of the ^{18}O levels at 5.530(2^-), 6.198(1^-), and 6.351(2^-) MeV. They also find that their experiments suggest that the 7.059 MeV of Ref. [7] is a 7.05-7.12 doublet. Their Coulomb computation of the 4^+ analog yields ~7.05 MeV. Our computation yields 7086(40) keV, with $\Gamma_p=34$ keV, in agreement with their suggestion. [In contrast to our method of employing a complete set of components, Hahn *et al.* [8] used only the ground state (g.s.) core, computed a single-particle change in excitation energy, and reduced that by a small spectroscopic factor. This amounts to assuming that remaining components provide no changes in excitation energy, a rather dubious assumption, generally.]

The lowest 3^+ state of ^{18}Ne is important [9] in nucleosynthesis via the $^{17}\mathrm{F}(p,\gamma)$ reaction, which can determine the $^{17}\mathrm{O}/^{18}\mathrm{O}$ ratio in explosive H burning. It could also be the principal source of ^{18}O and could lead to a breakout from the hot-CNO cycle. It is also a crucial element in the supermassive star (SMS) model used to explain the large amount of ^{26}Al in our galaxy, which unfortunately predicts a $^{17}\mathrm{O}/^{18}\mathrm{O}$ ratio much larger than observed. This prediction could be correct if there is a strong *s*-wave $^{17}\mathrm{F}(p,\gamma)$ resonance at ~400 keV. The energy of this state is not known with certainty.

We can use our procedure to estimate the location of the 3^+ level. In ^{18}O, this state—whose configuration is virtually pure (ds)—is at 5378 keV. Its predicted energy in ^{18}Ne does not depend on *c*, as no collective component is involved. The $2s_{1/2}$ component coupled to the $\frac{5}{2}^+$ g.s. gives $E_x(^{18}\mathrm{Ne})=4488$ keV, whereas $1d_{5/2}$ coupled to the $\frac{1}{2}^+$ first excited state produces 4775 keV, giving an average of 4631 keV for the expected position of the 3^+ state in ^{18}Ne, if it were pure $(1d_{5/2})(2s_{1/2})$. Addition of a small (2%) mixture of $(1d_{5/2})(1d_{3/2})$ (from a two-particle shell-model calculation [2]) raises this by 11 keV, to become 4642 keV. In fact, because any other small wave-function admixtures are unlikely to contain large $s_{1/2}$ components, such an admixture will only raise the excitation energy in ^{18}Ne. Its predicted width is 42 keV.

Garcia *et al.* [9] made a similar calculation for the $2s$ component coupled to the $\frac{5}{2}^+$ ground state finding 4.53 MeV, but they neglected the $1d_{5/2}$ coupled to the $\frac{1}{2}^+$ level of ^{17}O. They looked for this level with the $^{16}\mathrm{O}(^3\mathrm{He},n)$ reaction and report the possible presence of a very weak peak at 4.56 MeV, between the known 1^- and 0^+ levels at 4519 and 4590 keV. As a transistion to an unnatural parity level is forbidden in first order in a direct reaction a weak population was to be expected. The same forbiddenness is true for the $^{20}\mathrm{Ne}(p,t)$ reaction which failed [8] to find a 4.56 MeV level although a 3^+ excitation via $^{20}\mathrm{Ne}(p,d)^{19}\mathrm{F}(\frac{1}{2}^+)(d,t)^{18}\mathrm{Ne}(3^+)$ is possible. [A similar two-step process in $(^3\mathrm{He},n)$ is also possible.] In Fig. 11 of Hahn, *et al.* [8], the 20° $^{20}\mathrm{Ne}(p,t)$ spectrum exhibits a hint of a weak, broad peak at about 4.66 MeV. This range of excitation energy should be explored further.

The 3^+ level in ^{18}O at 5378 keV was seen in the $^{16}\mathrm{O}(t,p)^{18}\mathrm{O}$ reaction by Cobern *et al.* [10] with a strength similar to some weaker allowed states. The absence of a similar success in the $(^3\mathrm{He},n)$ experiment may be due to the fact that the (t,p) and $(^3\mathrm{He},n)$ Q values differ greatly (-1.7 and ~-8 MeV, respectively) which led at their bombarding energies to vastly different favored angular momentum transfers. The (^{3}He,n) experiment should be repeated for a bombarding energy near 18 MeV. This choice would roughly equalize the energies available above the Coulomb barrier.

The known level structure [7] of ^{18}Ne is such that if our computations are meaningful the 3^+ level may be part of a presently unresolved doublet with the experimental 4590 keV, 0^+ level, for which our calculated value is 4619 keV, only 23 keV away from the calculated 3^+ value. If the 3^+ level is at about 4.59 MeV, the resonance energy for ^{17}F(p,γ) would be about 670 keV, a result which Garcia *et al.* [9] point out reduces the rate of the ^{17}F(p,γ) reaction previously computed by two orders of magnitude.

III. CONCLUSIONS

For six known positive-parity levels of ^{18}Ne, our Coulomb-energy calculations agree with the known energies with an average discrepancy of -8 keV (absolute value deviations rms average is 35 keV). For 2_3^+, our calculated excitation energy of 5022 keV is lower than both of the known levels at 5090 and 5146 keV. Given the overall differences for the other states, we have a strong preference for 5090 as 2_3^+. We predict the ^{18}Ne 3^+ level at 4642 keV—virtually degenerate with 0_3^+. We suggest another investigation of ^{16}O(^{3}He,n), this time at around 18 MeV bombarding energy.

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