The $1d_{5/2}$ single-particle state and widths in ^{14}O and ^{15,16}F

H. T. Fortune

Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

(Received 18 February 2018; published 17 April 2018)

I have examined spectroscopic factors for predominantly $1d_{5/2}$ single-particle states in isospin multiplets having $A = 14-16$. Results indicate a serious problem with the width of the $5/2^+$ resonance in ^{15}F. Calculations provide recommended widths in ^{14}O and ^{16}F.

DOI: 10.1103/PhysRevC.97.044314

I. INTRODUCTION

The ground states (g.s.'s) of ^{17}O and ^{17}F are predominantly $1d_{5/2}$ single-particle (sp) states. In lighter nuclei, this is an excited state ($J_{\rm core} = 0$) or a multiplet ($J_{\rm core} \neq 0$). Here, I summarize information for these states in $A = 14-16$ nuclei, and then I address widths in ^{14}O, ^{15,16}F.

II. ANALYSIS AND RESULTS

In the reaction ^{16}O(d,p) ^{17}O, at energies of 25.4, 36.0, and 63.2 MeV, the g.s. spectroscopic factor is $S = 0.9(1)$ [1]. In ^{16}O(^{3}He,d) ^{17}F, S(g.s.) is 0.94 [2]. Until quite recently, the spectroscopic factors in ^{16}N and ^{16}F were poorly known. In the reaction ^{15}N(d,p) ^{16}N at $E_d = 5.0$, 5.5, and 6.0 MeV, S for all four of the so-called sp states was about 0.5 [3]—rather than near unity as expected. Recently, an investigation of the reaction ^{15}N(^{7}Li,^{6}Li)^{16}N reported $S(2^-) = 0.96(9)$ and $S(3^-) = 0.84(8)$ [4]. Those authors used those spectroscopic factors and mirror symmetry to compute widths in ^{16}F. In the latest compilation [5], those widths are listed as $\Gamma(2^-) = 40(30)$ and $\Gamma(3^-) < 15$, both in keV. Widths from other sources are summarized elsewhere [4,6]. The calculations of Ref. [4] produced widths of 3.66 ± 0.35 for 2^- and 11.2 ± 1.1 for 3^-, both in keV. A recent ^{15}O + p elastic scattering experiment [6] reported widths of 4.0(13) and 15.1(34) keV for 2^- and 3^-, respectively. I have computed sp widths in a Woods-Saxon potential well having geometric parameters of r_0, $a = 1.26$, 0.60 fm. The Coulomb potential was that of a uniform sphere with $r_{0c} = 1.40$ fm. I then computed expected widths from the expression $\Gamma_{\rm calc} = S\,\Gamma_{\rm sp}$. Results are listed in Table I, where they are compared with the earlier results.

In ^{15}F, the first-excited resonance is $5/2^+$, at $E_p = 2.785$ MeV. Various values have been reported for its width [7], but the best values are near 300 keV. Stefan *et al.* [8] report $\Gamma = 311(10)$ keV, whereas deGrancey, *et al.* [9] give $\Gamma = 305(12)$ keV. My computed sp width is $\Gamma_{\rm sp} = 294$ keV, with a small uncertainty. With an average experimental width of 303(10) keV, the resulting spectroscopic factor is $S = 1.03(4)$. By itself, this value does not present a problem. However, the other $T = 3/2$ $J^\pi = 5/2^+$ states in $A = 15$ nuclei have S near 0.70 [7,10] (Fig. 1). In the reaction ^{14}C(d,p) ^{15}C, S is 0.69 [11], to which I have assigned an uncertainty of 10%. For the other two nuclei, the widths and spectroscopic factors are related by the expression $\Gamma = C^2 S\Gamma_{\rm sp}$, where the squares of the isospin Clebsch-Gordan coefficient C^2 are 1/3 for ^{15}N and 2/3 for ^{15}O. Widths and S's are listed in Table II for these four nuclei [7]. The average for ^{15}C, ^{15}N, and ^{15}O is $S = 0.72(4)$, so that the difference between $S(^{15}$F) and the average S for the other three nuclei is 0.31(6), about 5.5σ away from zero.

I earlier explored the possibility of isospin mixing for the lowest $T = 3/2$ states in ^{15}N and ^{15}O, and I stated [10], "The $5/2^+$, $T = 3/2$ state has no discernible neutron or alpha width in ^{15}N and no alpha or g.s. proton width in ^{15}O, so any mixing there is very small." Thus, it would appear that either the width in ^{15}F is only about 2/3 as large as currently thought, or the extracted S in the three other nuclei are all too small by about the same factor. The newest width measurements in ^{15}F have no obvious problems, but it is unlikely that results for all three of the other nuclei are incorrect. Because of this large discrepancy, I have investigated the $d_{5/2}$ spectroscopic factors in another isospin multiplet, viz $A = 14$.

In ^{14}C, the 3^- and 2^- states at energies of 6.728 and 7.341 MeV [7] have large $d_{5/2}$ strength. In the ^{13}C(d,p) ^{14}C reaction, $S(3^-)$ is 0.65 and $S(2^-)$ is 0.72 [12]. The analogs at 8.907 and 9.509 MeV in ^{14}N are unbound, with widths of 16(2) and 41(2) keV for 3^- and 2^-, respectively [7]. With sp widths of 35 and 110 keV, these correspond to spectroscopic factors of 0.91(11) and 0.75(4), respectively. Various values have been reported for the widths of the mirror states at 6.280 and 6.769 MeV in ^{14}O [7,13–15]. These are listed in Table III and plotted in Fig. 2, where I have again assigned 10% uncertainty to S from (d,p). I have omitted the width of 103(6) keV [7] [$S = 1.94(11)$]. The weighted average of all these spectroscopic factors is 0.71(4) for 3^- and 0.72(4) for 2^-. The horizontal band in the figure represents the average of 0.715(25). We note that the overall agreement is good. Requiring S for 2^- and 3^- members of this isospin multiplet to be separately equal provides computed values for the widths in ^{14}O. They are 38(2) for 3^- and 94(5) for 2^-, both in keV. Thus, this isospin multiplet does not exhibit the behavior displayed for $A = 15$, $T = 3/2$.

Table IV lists reported energies and widths of the $5/2^+$ resonance in ^{15}F from various experiments [8,9,16–21]. Ironically, the very first one of 0.24(3) MeV [16] is close to the value indicated as necessary from the present analysis. All the other widths are significantly larger.

TABLE I. Results for $1d_{5/2}$ doublet in ^{16}N and ^{16}F (energies in MeV, widths in keV).

J^π	$E_x(^{16}\text{N})$[a]	$S(^{16}\text{N})$[b]	$E_p(^{16}\text{F})$[a]	Γ_{sp}[c]	Γ_{calc}[d]	Γ_{exp}[e]
2^-	0.0	0.96(9)	0.961	3.44	3.3(0.3)	4.0 (1.3)
3^-	0.298	0.84(8)	1.256	12.2	10.2(1.0)	15.1 (3.4)

[a]Ref. [5].
[b]Ref. [4].
[c]Present work.
[d]$\Gamma_{calc} = S\,\Gamma_{sp}$
[e]Ref. [6]; uncertainties are 1σ values.

TABLE II. Properties of lowest $5/2^+$, $T = 3/2$ states in $A = 15$ nuclei (energies in MeV, widths in keV).

	Experimental			Calculated	
Nucl.	E_x[a]	E_p	Γ[a]	Γ_{sp}	$S = \Gamma_{exp}/(C^2\Gamma_{sp})$[c]
^{15}C	0.74				0.69(7)[d]
^{15}N	12.522	2.315	58(4)	232	0.75(5)
^{15}O	12.255	2.645[b]	135(15)	300[b]	0.68(8)
^{15}F		2.785	303(10)	294	1.03(4)

[a]Ref. [7].
[b]For decay to the 0^+, $T = 1$ state of ^{14}N.
[c]$C^2 = 1/3, 2/3, 1$ for ^{15}N, ^{15}O, ^{15}F.
[d]From ^{14}C(d,p) [11].

TABLE III. Properties of lowest 3^- and 2^-, $T = 1$ states in $A = 14$ nuclei (energies in MeV, widths in keV).

Nucl.	J^π	E_x (exp.)[a]	E_p (exp.)	Γ_{exp}[a]	Γ_{sp}	$S = \Gamma_{exp}/(C^2\Gamma_{sp})$	Γ_{calc}
^{14}C	3^-	6.728				0.65[e]	
	2^-	7.341				0.72[e]	
^{14}N	3^-	8.907	1.356	16(2)	35	0.91(11)	12.4(7)
	2^-	9.509	1.958	41(2)	110	0.75(4)	39.6(22)
^{14}O	3^-	6.280	1.652	103(6)	53	1.94(11)	38(2)
				50(6)[b]		0.94(11)	
				42(2)[c]		0.79(4)	
				25(3)[d]		0.47(6)	
	2^-	6.769	2.141	107(40)[b]	130	0.82(31)	94(5)
				90(5)[c]		0.69(4)	

[a]Ref. [7], unless noted otherwise.
[b]Ref. [13].
[c]Ref. [14].
[d]Ref. [15].
[e]From ^{13}C(d,p), Ref. [12].

TABLE IV. Energies and widths (both in MeV) of first $5/2^+$ resonance in ^{15}F.

Reference	E_p	Γ
16	2.8(2)	0.24(3)
17	2.67(10)	0.5(2)
18	2.853(45)	0.34
19	2.80(5)	0.38(10)
20	2.795(45)	0.32(6)
21	2.810(20)	0.30(6)
8	2.78(1)	0.311(10)
9	2.763(9)(10)	0.305(9)(10)
9, recommended average	2.794(16)	0.301(16)
Used in present analysis	2.785	0.303(10)

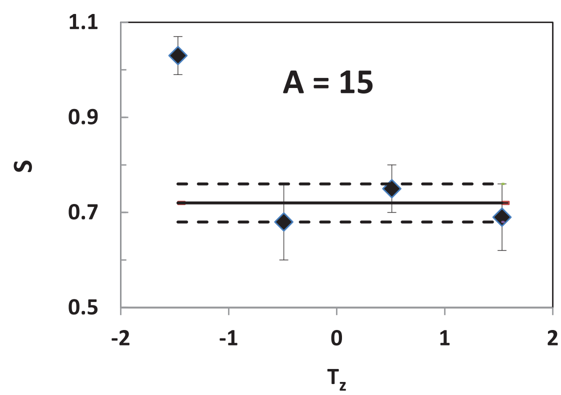

FIG. 1. Spectroscopic factors [plotted vs. $T_z = (N-Z)/2$] for the lowest $5/2^+$ states for $A = 15$, $T = 3/2$ nuclei.

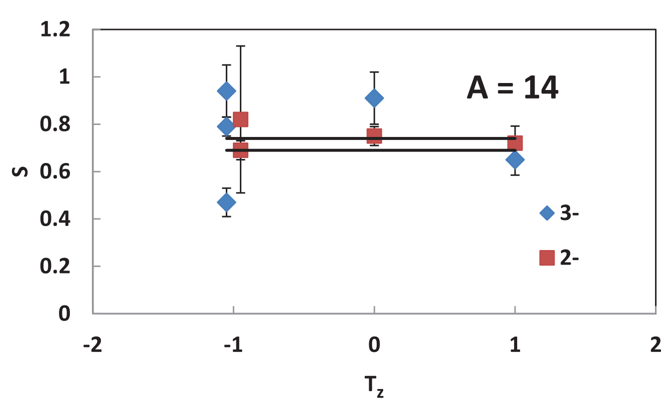

FIG. 2. As Fig. 1, but for lowest 3^- (diamonds) and 2^- (squares) states for $A = 14$, $T = 1$.

III. SUMMARY

I have examined spectroscopic factors for predominantly $1d_{5/2}$ single-particle states in isospin multiplets having $A =$ 14, 15, and 16. Calculations provide recommended widths in ^{14}O and ^{16}F that are in good agreement with experimental values. Results indicate a serious problem with the width of the $5/2^+$ resonance in ^{15}F. Most recent experimental values of this width are about 1.5 times as large as expected from spectroscopic factors for the lowest $5/2^+$ state in other $A = 15$, $T = 3/2$ nuclei.

[1] M. D. Cooper, W. F. Hornyak, and P. G. Roos, Nucl. Phys. A **218**, 249 (1974).
[2] H. T. Fortune, L. R. Medsker, J. D. Garrett, and H. G. Bingham, Phys. Rev. C **12**, 1723 (1975).
[3] W. Bohne, J. Bommer, H. Fuchs, K. Grabisch, H. Kluge, and G. Roschert, Nucl. Phys. A **196**, 41 (1972).
[4] Z. D. Wu *et al.*, Phys. Rev. C **89**, 054315 (2014).
[5] D. R. Tilley, H. R. Weller, and C. M. Cheves, Nucl. Phys. A **564**, 1 (1993).
[6] D. W. Lee, K. Perajarvi, J. Powell, J. P. O'Neil, D. M. Moltz, V. Z. Goldberg, and J. Cerny, Phys. Rev. C **76**, 024314 (2007).
[7] F. Ajzenberg-Selove, Nucl. Phys. A **523**, 1 (1991).
[8] I. Stefan *et al.*, Phys. Rev. C **90**, 014307 (2014).
[9] F. de Grancey *et al.*, Phys. Lett. B **758**, 26 (2016).
[10] H. T. Fortune, Phys. Rev. C **74**, 054310 (2006).
[11] J. D. Goss, P. L. Jolivette, C. P. Browne, S. E. Darden, H. R. Weller, and R. A. Blue, Phys. Rev. C **12**, 1730 (1975).
[12] R. J. Peterson, H. C. Bhang, J. J. Hamill, and T. G. Masterson., Nucl. Phys. A **425**, 469 (1984).
[13] A. Negret *et al.*, Phys. Rev. C **71**, 047303 (2005).
[14] T. Teranishi *et al.*, Phys. Lett. B **650**, 129 (2007).
[15] Y. B. Wang, B. X. Wang, X. Qin, X. X. Bai, B. Guo, C. Jiang, Y. J. Li, Z. H. Li, G. Lian, J. Su, S. Zeng, and W. P. Liu, Phys. Rev. C **77**, 044304 (2008).
[16] W. Benenson, E. Kashy, A. G. Ledebuhr, R. C. Pardo, R. G. H. Robertson, and L. W. Robinson, Phys. Rev. C **17**, 1939 (1978).
[17] G. J. KeKelis, M. S. Zisman, D. K.Scott, R. Jahn, D. J. Vieira, J. Cerny, and F. Ajzenberg-Selove, Phys. Rev. C **17**, 1929 (1978).
[18] W. Peters *et al.*, Phys. Rev. C **68**, 034607 (2003).
[19] A. Lepine-Szily *et al.*, Nucl. Phys. A **734**, 331 (2004); (private communication).
[20] V. Z. Goldberg, G. G. Chubarian, G. Tabacaru, L. Trache, R. E. Tribble, A. Aprahamian, G. V. Rogachev, B. B. Skorodumov, and X. D. Tang, Phys. Rev. C **69**, 031302(R) (2004).
[21] F. Q. Guo *et al.*, Phys. Rev. C **72**, 034312 (2005).