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Di-proton decay of the 6.15 MeV 1^- state in ^{18}Ne

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The widths for one- and two-proton decay of the 1_2^- state in ^{18}Ne are calculated. Shell-model wave functions are used to obtain the spectroscopic factors. The *R*-matrix theory of Barker which incorporates the final-state interaction between the two protons is used for the di-proton decay model. The calculated widths for both one- and two-proton decay are in qualitative agreement with experiment. We find that the decay width for sequential two-proton decay through the ghost of the $1/2^+$ bound state in ^{17}F is comparable to the width of the direct di-proton decay.

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Nuclei have been observed to decay by a variety of processes which include fission, beta decay, gamma decay, alpha decay, and proton decay. Di-proton (^{2}He) decay which involves the simultaneous emission of two protons [1,2] is perhaps the next on this list, but it has proven to be the most elusive. The optimal condition for this mode of decay is that single-proton decay $^{A}Z\rightarrow^{(A-1)}(Z-1)$ be energetically forbidden, and that the Q value for two-proton decay $^{A}Z\rightarrow^{(A-2)}(Z-2)$ be in a narrow range such that its lifetime or decay width is experimentally accessible. The pairing interaction contribution to the nuclear binding energy gives the possibility for this situation to occur. However, it may also be possible to observe diproton decay in a situation where the single-proton decay is also allowed. Such a case has recently been suggested in the decay of a 1^- state at 6.15 MeV in ^{18}Ne [3]. The decay of this state is dominated by single-proton decay to the low-lying bound states of ^{17}F, but there are no narrow intermediate states in ^{17}F which can contribute to the two-proton emission to the ground state of ^{16}O. The experimental width for the two-proton emission is 21 ± 3 eV if a di-proton decay model is assumed and 57 ± 6 eV assuming a sequential (democratic) decay model [3].

In this Rapid Communication we present the first microscopic shell-model calculations for the two-proton decay of this 1^- state in ^{18}Ne using the *R*-matrix models of Barker for di-proton decay [4] and sequential decay [5]. We first discuss the dominant one-proton decay branch to the low-lying bound states of ^{17}F. Next we discuss sequential proton emission through the tail of a high-lying $3/2^+$ state and the ghost of the $1/2^+$ bound state in ^{17}F. Finally the calculation for the di-proton decay is presented. Our results agree with experiment for both one- and two-proton decay to within a factor of two, and suggest that the two-proton decay is a combination of sequential and direct processes.

The shell-model wave functions are obtained in a model space which includes the $0s$,$0p$,$1s0d$, and $1p0f$ orbits. ^{16}O is treated as an s^4p^{12} closed shell, and the lowest-lying positive parity states of ^{17}F and ^{18}Ne are taken as $s^4p^{12}(sd)^1$ and $s^4p^{12}(sd)^2$ configurations, respectively. The negative parity states in ^{18}Ne are treated as $1\hbar\omega$ excitations of the form $s^4p^{11}(sd)^3$ and $s^4p^{12}(sd)^1(pf)^1$. With these configurations the ^{18}Ne to ^{16}O decay involves the emission of two protons in an $(sd)(pf)$ configuration. The state of interest is the second 1^- state in ^{18}Ne.

The wave functions are obtained with several Hamiltonians which have been designed for use in this type of model space, namely the MK interaction [6] and the WBP and WBT interactions [7]. The MK wave functions have been used for a number of studies of the analogue nucleus ^{18}O including ^{18}N$(\beta^-)^{18}$O [8], ^{18}O$(\pi,\pi')^{18}$O [9], and ^{18}O$(e,e')^{18}$O [10]. As shown in Table I, the calculated energies of the lowest five 1^- states are in reasonable agreement with the energies found in the analogue nucleus ^{18}O. (The MK interaction is designed mainly for the relative spacing, and thus the MK excitation energies are given relative to the lowest 1^- state in ^{18}O.) These low-lying 1^- states are dominated by the $s^4p^{11}(sd)^3$ configuration. The smaller $s^4p^{12}(sd)^1(pf)^1$ component is the one responsible for one- and two-proton decay, and the probability of this component for the various interactions is given in Table I labeled by $\%(sd)(pf)$.

The dominant mode of decay for the 1_2^- state in ^{18}Ne is by one-proton emission to the $5/2^+$ ground state ($Q_{1p}=2.228$ MeV) and $1/2^+$ first excited state ($Q_{1p}=1.733$ MeV) of ^{17}F. Single-particle widths Γ^{sp} are obtained [5] from the resonance energy in a Woods-Saxon well with a depth chosen to reproduce Q_{1p}. The decay to the ground state can go by *f*-wave emission ($\Gamma^{sp}=8.03$ keV) or *p*-wave emission ($\Gamma^{sp}=1270$ keV). The decay to the excited state can go by *p*-wave emission ($\Gamma^{sp}=627$ keV). The

TABLE I. Total and (5 0) intensities of $(1s0d)(1p0f)$ for the first five 1^- states for the MK, WBP, and WBT interactions. The excitation energies are compared to the experimental energies in ^{18}O.

Ex (MeV)[a]				MK		WBP		WBT	
Expt	MK	WBP	WBT	%$(sd)(pf)$	%(5 0)	%$(sd)(pf)$	%(5 0)	%$(sd)(pf)$	%(5 0)
4.46	4.46	4.46	4.54	1.93	0.20	1.64	0.49	2.20	0.66
6.20	6.83	6.71	6.98	17.90	3.84	9.54	2.13	11.28	6.73
7.62	7.63	7.43	7.46	4.62	1.29	8.44	6.63	8.10	1.34
8.04	8.21	7.65	7.70	8.31	3.51	2.67	0.44	1.90	0.83
9.00	9.01	9.41	9.30	30.52	18.29	16.56	9.03	22.49	14.75

[a]The MK energies are given relative to that of the lowest experimental state. The WBP and WBT are absolute excitation energies.

shell-model spectroscopic factors and the resulting decay widths $\Gamma = C^2 S \Gamma^{sp}$ are given in Table II. The widths all turn out to be about 30 keV compared with the known width of 50 ± 5 keV [3], but the individual contributions are very different. The width obviously depends mainly on the *p*-wave admixtures which are small and quite variable. Thus we conclude that there is about a factor of two uncertainty in the theoretical spectroscopic factors and that the agreement with experiment is satisfactory.

Although there are no unbound states present in the energy window for the two-proton decay of the 1_2^- state in ^{18}Ne, sequential two proton decay may proceed through the tails of states outside the window. There are two possibilities, one is through the ghost associated with the $1/2^+$ bound state [11] and the other is through the low-energy tail of the broad $3/2^+$ state at 5.0 MeV which has a width of 1.5 MeV. This large width indicates that the $3/2^+$ state is dominated by the $0d_{3/2}$ single-particle component. The spectroscopic factors for the decay of the ^{18}Ne 1^- state to the $3/2^+$ state are given in Table II. Barker [5] has given the *R*-matrix formulation for the sequential emission through a broad intermediate state. Application of this method with the spectroscopic factors of Table II gives widths of about 1 meV for $1p$ wave emission to the $3/2^+$ state and much less for $0f$ emission. Thus the sequential decay through the tail of the $3/2^+$ state gives a negligible contribution to the width.

The ghost of the $1/2^+$ bound state turns out to be more important. Its peak is estimated to be at about 2.4 MeV in ^{17}F and it is very broad [11], so that decay through the ghost would be interpreted [3] as democratic decay. The ratio of the one-proton decay width to the ghost relative to the $1/2^+$ bound state comes out to be 6.3×10^{-4}, leading to the widths given at the bottom of Table II. The calculated width for the sequential two-proton decay through the $1/2^+$ ghost, 9–19 eV, are comparable in size to the observed two-proton width (57 ± 7 eV for democratic decay) which implies that this channel can be important. (The decay width to the $1/2^+$ bound state is renormalized by a factor of 0.81 by the presence of the ghost state—this factor is not included in Table II.)

For the di-proton decay, decay models have recently been developed [4,12] which are much more realistic than the original two-body cluster estimates [2]. We use the *R*-matrix model [4] which incorporates the final-state interaction be-

TABLE II. Spectroscopic factors for proton decay of the 1_2^- state of ^{18}Ne for each of the interactions. The second grouping gives the widths for each of the channels after combining the spectroscopic factors, including an extra factor of $(18/17)^3$, and single-particle widths. The last two lines are the total widths for single-proton and sequential two-proton decay, respectively.

	Channel	MK	WBP	WBT
S	$5/2^+\times0f_{7/2}$	0.1374	0.0646	0.0641
	$5/2^+\times0f_{5/2}$	0.0026	0.0007	0.0009
	$5/2^+\times1p_{3/2}$	0.0073	0.0011	0.0060
	$1/2^+\times1p_{3/2}$	0.0186	0.0215	0.0090
	$1/2^+\times1p_{1/2}$	0.0034	0.0184	0.0104
	$3/2^+\times0f_{5/2}$	0.0097	0.0047	0.0058
	$3/2^+\times1p_{3/2}$	0.00002	0.00003	0.00017
	$3/2^+\times1p_{1/2}$	0.00005	0.00023	0.00058
Γ(keV)	$5/2^+\times0f$	1.33	0.62	0.62
(kev)	$5/2^+\times1p$	11.0	1.66	9.04
	$1/2^+\times1p$	16.4	29.7	14.4
Total Γ(keV)		28.7	32.0	24.1
Γ(eV)	$1/2^+$(ghost)$\times1p$	10.3	18.7	9.1

tween the two protons in terms of the s-wave phase shift. This model provides the observed width Γ as a function of the reduced width γ^2 [Eq. (1) of [4]]. When γ^2 is small the denominator in Eq. (1) of [4] is near unity and the width is given in the R-matrix model by

$$\Gamma(Q_{2p}) = 2\gamma^2 \int_0^{Q_{2p}} P(Q_{2p}-U)\rho(U)dU, \qquad (1)$$

where P is the penetration factor and $\rho(U)$ is a density of states function for the two protons. In the simple cluster model for the decay, the integral is replaced by $P(Q_{2p})$. The reduced width γ^2 is related to the spectroscopic factor, S, by [5] $\gamma^2 = S(\hbar^2/Ma^2)\theta_{sp}^2$, where θ_{sp}^2 is the single-particle dimensionless reduced width [Eq. (16) of [5]], M is the reduced mass, and a is the channel radius taken as in Ref. [4] by the conventional formula $a = 1.45(A_1^{1/3}+A_2^{1/3})$ fm with $A_1 = 16$ and $A_2 = 2$. This R-matrix model gives an effective penetration factor, the integral in Eq. (1) with $Q_{2p} = 1.628$ MeV, of 1.30×10^{-4}. If the final-state interaction between the two protons is ignored one would obtain the much larger value $P(Q_{2p}) = 1.31\times10^{-2}$. With the single-particle dimensionless reduced width for the $2p$ state of ^{2}He $\theta_{sp}^2 = 0.65$, the total width for diproton decay is given by $\Gamma = 133\,S$ eV, where S is the spectroscopic factor.

To calculate the spectroscopic factor we project the shell-model wave function onto the $0s$ internal (relative) wave function of the $(sd)(pf)$ pair using harmonic oscillator wave functions [13]. Then,

$$S = \left(\frac{18}{16}\right)^5 G^2(sd,pf)A^2(5\,0) = 1.126A^2(5\,0), \qquad (2)$$

where $G^2 = 5/8$ and $A(\lambda=5,\mu=0)$ is the amplitude of the only $(sd)(pf)$ configuration (with $L=1, S=0$) in the SU3 basis relevant to $L=1$ di-proton emission. The cluster spectroscopic factor defined above is found immediately by calculating the two-particle $(5\,0)$ amplitude from the shell-model wave functions in an SU3 basis. In the more usual jj basis such as obtained in the shell-model code OXBASH, the spectroscopic factor is obtained by multiplying the two-body overlap amplitudes by the factor

$$(i)^{l_1+l_2}\langle(2\,0)l_1(3\,0)l_2||(5\,0)1\rangle \begin{pmatrix} l_1 & 1/2 & j_1 \\ l_2 & 1/2 & j_2 \\ 1 & 0 & 1 \end{pmatrix}, \qquad (3)$$

where the $(i)^l$ factor accounts for the difference between the SU3 phase convention and the jj phase convention used in OXBASH.

Note in Table I that the second 1^- level of interest does have a significant $(sd)(pf)$ content for all three calculations. However, the $(5\,0)$ intensities show considerable variation, with spectroscopic factors of 0.043, 0.024, and 0.075 for MK, WBP, and WBT, respectively. When combined with $\Gamma = 133\,S$ eV, we obtain di-proton decay widths of 6, 3, and 10 eV for MK, WBP, and WBT respectively. These are somewhat smaller than the experimental width of 21 ± 3 eV obtained if a ^{2}He decay model is assumed [3]. A three-body decay model for di-proton decay has been presented by Grigorenko *et al.* [12]. However, it is not clear how the complex nuclear structure which is reflected in the spectroscopic factor enters into the three-body model, and hence it is not easy to make a comparison to the R-matrix model.

In summary, we have presented the first microscopic calculations for the one- and two-proton decays of the 6.15 MeV 1^- state in ^{18}Ne. The calculated one-proton decay width is within a factor of two of the observed width. For the two-proton decay we find that sequential decay through the ghost of the $1/2^+$ state is within a factor of three of the observed width obtained with the assumption of democratic decay [3]. The calculated width for ^{2}He emission is only about a factor of two smaller than that for sequential decay indicating that the observed decay may be a combination of the two processes. Given that the spectroscopic factors are small, and that the decay models involve some approximations, the agreement with experiment is satisfactory. More detailed experimental results on the two-proton decay are required to determine the fraction of the decay which can be attributed to the special process of ^{2}He decay.

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