Two-proton sequential decay from excited states of ^{18}Ne

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Abstract Two-proton radioactivity from ^{18}Ne is discussed in terms of sequential decay. The branch ratios for one-proton emission from excited states are calculated, which including spectroscopic factors, obtained from a Shell-model calculation with realistic interactions. The branch ratios show that the two-proton emission from the 1^- state of ^{18}Ne at 7.94 MeV is most likely to go through the sequential decay. The same mechanism is discussed for other excited states at higher energy by different interactions.

Key words Two-proton radioactivity, Nuclear shell model, Branch ratios

1 Introduction

Proton radioactivity, experimentally observed as a decay from the ground state, at GSI in 1981, has provided very important information on the structure of nuclei beyond the proton drip-line. The more complicated decaying mode, two-proton radioactivity, proposed 50 years ago in a classical article[1] opened a new window to investigate nucleon-nucleon correlations and the structure of atomic nuclei. In 2002, the simultaneous emission of two-protons was for the first time observed in the decay of ^{45}Fe by Pfutzner, Giovinazzoin experiments at GSI and GANIL[2,3]. Research in the field flourished after this breakthrough, and to date ^{54}Zn[4], ^{48}Ni[5], ^{19}Mg[6], ^{16}Ne[7], ^{17}Ne[8], ^{18}Ne[9], ^{10}C[10], ^{14}O[11] and ^{29}S[12] have been found to exhibit two-proton emission. Several theoretical approaches such as Diproton model[13,14], R-matrix approach[15], continuum shell model[16], adiabatic hyperspherical approach[17], and the quantum three body cluster approach[18], where the tunneling through the barrier is treated in a dynamical way, were applied to the problem.

There are two different decay modes for simultaneous two-proton emission: (1) three-body direct breakup involving an uncorrelated emission of the two protons, usually referred to as democratic emission. (2) ^{2}He cluster emission where a pair of protons, correlated in a quasi-bound ^1S configuration, breakup, when emitted into two protons (diproton emission). The two protons have strong angular and energy correlations. The ^{2}He appears as a resonance at 20 MeV/c in the two-proton relative momentum distribution[19]. The microscopic calculations for the one- and two-proton decays of the 6.15 MeV 1^- state of ^{18}Ne had been presented in the Ref.[20]. It was found that for the two-proton the sequential decay through a ghost of the $1/2^+$ state is within a factor of three of the observed width obtained with the assumption of democratic decay. The calculated width for diproton 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. In the excitation-energy spectrum of ^{18}Ne in the Ref.[9], it's strange that some states can be seen in the two-proton emission ^{18}Ne→^{16}O+2p channel and not in the one-proton emission ^{18}Ne→^{17}F+p channel. That means that in these states we cannot find the ^{17}F in ground state. So the sequential decay for two protons is most likely to occur in these states.

In this paper we present the microscopic shell-model calculations for sequential two-proton decay from excited states in ^{18}Ne by some different Hamiltonians.

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2 Calculation and discussion

The spectroscopic factor is the most important quantity needed to obtain the decay width. In order to calculate it, we perform a shell-model calculation to get the wave functions for ^{18}Ne. The model space was used, including the 0s, 0p, 1s0d and 1p0f orbits. ^{16}O is treated as a s^4p^{12} closed shell, and the low-lying positive parity states of ^{17}F and ^{18}Ne are taken as $s^4p^{12}(sd)^1$ and $s^4p^{12}(sd)^2$. The low-lying negative parity states of ^{17}F and ^{18}Ne are treated as 1 ω excitations of the form $s^4p^{11}(sd)^2$, $s^4p^{12}(pf)^1$ and $s^4p^{11}(sd)^3$, $s^4p^{12}(sd)^1(pf)^1$. So the emitted protons in the ^{18}Ne and ^{17}F are coming from (sd)(pf) shells. Two Hamiltonians designed for those types of model space are chosen for calculating the wave functions, namely the WBP and WBT interactions[21]. We use a simply shell-model code by our group, in this code the spurious states are removed by the usual method[22] by adding a center-of-mass Hamiltonian to the interaction.

The calculated excited energies of these low-lying states are shown in Fig.1. Some states are in reasonable agreement with the energies found in ^{18}Ne. The low-lying negative states are dominated by the $s^4p^{11}(sd)^3$ configuration, but the smaller s^4p^{12} $(sd)^1(pf)^1$ component is the one responsible for one- and two-proton decay. The shell-model spectroscopic factors are obtained by the wave functions of ^{18}Ne and ^{17}F. The decays from the positive states of ^{18}Ne to the positive states of ^{17}F and from the negative states of ^{18}Ne to the negative states of ^{17}F can go by 0d-shell wave emission or 1s-shell wave emission. The decays from the positive states of ^{18}Ne to the negative states of ^{17}F and from the negative states of ^{18}Ne to the positive states of ^{17}F can go by 0f-shell wave emission or 1p-shell wave emission. Because the $s^4p^{11}(sd)^3$ component in ^{18}Ne is quite larger than that of $s^4p^{12}(sd)^1(pf)^1$, the spectroscopic factors are larger in the channel of positive states in ^{18}Ne.

According to the scattering theory, the half-life for decay from initial state i to a final state f by one particle emission is given by:

$$T_{1/2} = \hbar \ln 2 / \Gamma_j^{if} \tag{1}$$

where the decay width can be found from the relation[25,26]:

$$\Gamma_j^{if} = S_j^{if}\Gamma_j = S_j^{if}\frac{2k\alpha_j^2}{m} \tag{2}$$

S_j^{if} is spectroscopic factor which corresponds to the probability that taking away a particle j with angular momentum j from an initial state i, will lead to a final state f. α_j is the asymptotic normalization of the proton single particle wave function in a state of spin j.

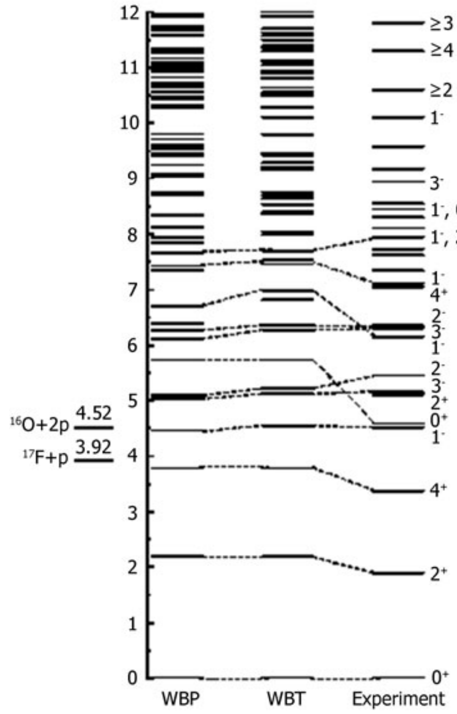

Fig.1 WBP and WBT predictions for the low-lying T=1 energy spectrum of ^{18}Ne. Some levels are labeled by J^π and E_x. The experimental data[23, 24] are presented on the right column. The J^π of levels which are not label are unknown.

The total width for decay is a sum of partial widths:

$$\Gamma_{\rm Tot}^{i} = \sum_{jf}\Gamma_j^{if} \tag{3}$$

The branching ratios are simply the ratio between a partial decay width and the total one:

$$\mathrm{Br}^{if} = \frac{\sum_j \Gamma_j^{if}}{\Gamma_{\rm Tot}^{i}} \tag{4}$$

For the fourth 1^- state at 7.94 MeV in ^{18}Ne, we find that the spectroscopic factors decaying to the $1/2^-$ third excited state (Q_{1p} = 0.914 1 MeV) is quite larger than that decaying to the $5/2^+$ ground state (Q_{1p} = 4.018 4 MeV) of ^{17}F. The spectroscopic factors and the widths for each of the channels are shown in Table 1. In this table, we can find the branch ratio that decays to $1/2^-$ state is larger than those decays to the ground state and the first ground state because it has larger spectroscopic factor even though it has smaller single-particle width. We can conclude that the 7.94 MeV 1^- state is most likely to be the best candidate for two-proton sequential decay. That is why it can be seen in the two-proton emission channel and not in the one-proton one. There are other states in this situation, like the 3^- state around 9–10 MeV (9.809 MeV for WBP and 10.099 MeV for WBT) and the 5^- state near 13 MeV (13.412 MeV for WBP and 13.200 MeV for WBT).

Table 1 Spectroscopic factors from the state $J^{\pi}=1^-$ of ^{18}Ne at E_x = 7.94 MeV. The channel $5/2^+\otimes$0f7/2 means that the emitted proton is from the 0f7/2 shell and decay to the $5/2^+$ state in ^{17}F. The last line is the total widths for single-proton

	WBP	WBT	Expt.	
E_x / MeV	7.648 0	7.698 6	7.94	
Channel	Spectroscopic factor			
	WBP	WBT	Γ_{sp} / keV	
$5/2^+\otimes$0f7/2	0.010 61	0.003 52	129	
$5/2^+\otimes$0f5/2	0.010 11	0.007 65	101	
$5/2^+\otimes$1p3/2	0.001 01	0.004 28	2 818	
$1/2^+\otimes$1p3/2	0.003 34	0.002 23	2 239	
$1/2^+\otimes$1p1/2	0.000 13	0.000 13	2 188	
$1/2^-\otimes$0d3/2	0.001 06	0.005 25	2	
$1/2^-\otimes$1s1/2	0.091 86	0.240 19	122	
	Γ_{WBP}	Γ_{WBT}	Br_{WBP}	Br_{WBT}
$5/2^+\otimes$(0f+1p)	5	13	0.216	0.277
$1/2^+\otimes$1p	8	5	0.32	0.11
$1/2^-\otimes$(0d+1s)	11	29	0.464	0.613
Total Γ	24	47	Expt. ≤ 50 keV	

3 Conclusion

We have presented some preliminary results of the proton decay branch ratios and decay width in ^{18}Ne using a shell-model calculation. The results obtained for the branch ratio from the 1^- state at 7.94 MeV in ^{18}Ne show that this state is most likely to be a candidate for sequential two-proton decay. The 3^- and the 5^- states can also be candidates for the same process.

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