Two-proton sequential decay from excited states of 18Ne (postprint)

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Full Text

Preamble

Two-proton sequential decay from excited states of 18Ne

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Abstract

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

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

Introduction

Proton radioactivity, first experimentally observed as ground-state decay at GSI in 1981, has provided crucial information on the structure of nuclei beyond the proton drip line. The more complex decay mode of two-proton radioactivity, proposed 50 years ago in a seminal article [1], opened a new window on nucleon-nucleon correlations and nuclear structure. In 2002, the simultaneous emission of two protons was observed for the first time in the decay of 45Fe by Pfützner, Giovinazzo, and collaborators in experiments at GSI and GANIL [2,3].

Research in this field flourished following this breakthrough, and to date 54Zn [4], 48Ni [5], 19Mg [6], 16Ne [7], 17Ne [8], 18Ne [9], 10C [10], 14O [11], and 29S [12] have been found to exhibit two-proton emission. Several theoretical approaches have been applied to this problem, including the di-proton model [13,14], R-matrix approach [15], continuum shell model [16], adiabatic hyperspherical approach [17], and the quantum three-body cluster approach [18], where tunneling through the barrier is treated dynamically. There are two distinct decay modes for simultaneous two-proton emission: (1) three-body direct breakup involving uncorrelated emission of the two protons, commonly referred to as democratic decay; and (2) 2He cluster emission, where a pair of protons correlated in a quasi-bound 1S configuration breaks up upon emission (di-proton emission). The two protons exhibit strong angular and energy correlations, with the 2He appearing as a resonance at 20 MeV/c in the two-proton relative momentum distribution [19].

Microscopic calculations for the one- and two-proton decays of the 6.15 MeV 1^- state of 18Ne were presented in Ref. [20]. It was found that for two-proton emission, sequential decay through a ghost of the $1/2^+$ state is within a factor of three of the democratic decay assumption. The calculated width for di-proton emission is only about a factor of two smaller than that for sequential decay, indicating that the observed decay may be a combination of both processes. In the excitation-energy spectrum of 18Ne from Ref. [9], it is notable that some states appear in the two-proton emission channel (18Ne → 16O + 2p) but not in the one-proton emission channel (18Ne → 17F + p). This suggests that 17F is not produced in its ground state in these decays, making sequential decay the most likely mechanism for two-proton emission from these states.

In this paper, we present microscopic shell-model calculations for sequential two-proton decay in 18Ne from excited states using different Hamiltonians.

2 Calculation and Discussion

The spectroscopic factor is the most important quantity needed to obtain the decay width. To calculate it, we perform a shell-model calculation to obtain the wave functions for 18Ne. The model space includes the 0s, 0p, 1s0d, and 1p0f orbits, with 16O treated as a closed s^4p^{12} shell. The low-lying positive-parity states of 17F and 18Ne are described as $s^4p^{12}(sd)^1$ and $s^4p^{12}(sd)^2$ configurations, while the low-lying negative-parity states are treated as $1\hbar\omega$ excitations of the forms $s^4p^{11}(sd)^2$, $s^4p^{12}(pf)^1$ and $s^4p^{11}(sd)^3$, $s^4p^{12}(sd)^1(pf)^1$. Thus, the emitted protons in 18Ne and 17F originate from the (sd)(pf) shells. Two Hamiltonians designed for these model spaces are selected for calculating the wave functions: the WBP and WBT interactions [21]. We employ a simple shell-model code developed by our group, in which spurious states are removed by the standard method [22] of adding a center-of-mass Hamiltonian to the interaction.

The calculated excitation energies of these low-lying states are shown in [Figure 1: see original paper]. Some states are in reasonable agreement with the experimental energies found in 18Ne. The low-lying negative-parity states are dominated by the $s^4p^{11}(sd)^3$ configuration, but the smaller $s^4p^{12}(sd)^1(pf)^1$ component is responsible for one- and two-proton decay. The shell-model spectroscopic factors are obtained from the wave functions of 18Ne and 17F.

Decays from positive-parity states of 18Ne to positive-parity states of 17F, and from negative-parity states of 18Ne to negative-parity states of 17F, can proceed via 0d-shell wave emission or 1s-shell wave emission. Decays from positive-parity states of 18Ne to negative-parity states of 17F, and from negative-parity states of 18Ne to positive-parity states of 17F, can proceed via 0f-shell wave emission or 1p-shell wave emission. Because the $s^4p^{11}(sd)^3$ component in 18Ne is much larger than that of $s^4p^{12}(sd)^1(pf)^1$, the spectroscopic factors are larger in channels involving positive-parity states in 18Ne.

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

$$\ln 2/T_{1/2} = \Gamma$$

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

$$\Gamma_{if} = S^j_{if}\Gamma^j_{sp}$$

Here S^j_{if} is the spectroscopic factor corresponding to the probability that removing a particle j with angular momentum j from an initial state i will lead to a final state f, and Γ^j_{sp} is the single-particle width. α_j is the asymptotic normalization of the proton single-particle wave function in a state of spin j.

[Figure 1: see original paper] shows WBP and WBT predictions for the low-lying $T = 1$ energy spectrum of 18Ne. Some levels are labeled by J^π and E_x. The experimental data [23,24] are presented in the right column. The J^π of levels that are not labeled are unknown.

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

$$\Gamma = \sum \Gamma_{if}$$

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

$$B_{if} = \Gamma_{if}/\Gamma$$

For the fourth 1^- state at 7.94 MeV in 18Ne, we find that the spectroscopic factor for decay to the $1/2^-$ third excited state ($Q_{1p} = 0.9141$ MeV) is considerably larger than that for decay to the $5/2^+$ ground state ($Q_{1p} = 4.0184$ MeV) of 17F. The spectroscopic factors and widths for each channel are shown in . From this table, we can see that the branching ratio for decay to the $1/2^-$ state is larger than those for decay to the ground state and first excited state because it has a larger spectroscopic factor, even though it has a smaller single-particle width. We conclude that the 7.94 MeV 1^- state is the most likely candidate for two-proton sequential decay. This explains why it can be observed in the two-proton emission channel but not in the one-proton channel. Other states in this situation include 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).

Spectroscopic factors from the state $J^\pi = 1^-$, $E_x = 7.94$ MeV. The channel $5/2^+$ proton is from the $0f_{7/2}$ shell and decays to the $5/2^+$ ground state in 17F. The last line shows the total widths for single-proton emission from 18Ne. $\otimes 0f_{7/2}$ means that the emitted proton originates from the $0f_{7/2}$ orbit.

E_x (MeV)	Channel	$\otimes 0f_{7/2}$	$\otimes 0f_{5/2}$	$\otimes 1p_{3/2}$	$\otimes 1p_{1/2}$	$\otimes 0d_{3/2}$	$\otimes 1s_{1/2}$	Expt.
Spectroscopic factor								
Γ_{sp} (keV)								
$\otimes(0f+1p)$								
$\otimes(0d+1s)$								
Total Γ								$\leq$ 50 keV
BrWBP								
BrWBT								

3 Conclusion

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

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