論文の内容の要旨

Quasi-free proton knokout reaction of ^{23,25}F

(^{23,25}F 核の準弾性(p,2p)ノックアウト反応)

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Introduction

The change of neutron-shell structure in fluorine isotopes due to the single $1d_{5/2}$ proton can be seen in the difference of the neutron dripline [1]. We aim to study the change of the neutron sd-shell structure by the proton in neutron-rich ^{23}F and ^{25}F nucleus using proton knockout spectroscopy. If the neutron-shell structures of fluorine and oxygen are the same, the spectroscopic factor of the $1d_{5/2}$ proton should not be fragmented and close to the common quenching factor of ~0.7 [2]. The effect of the proton to the neutron-shell structure can be studied through the spectroscopy.

Experimental Setup and Data Analysis

An inverse kinematics was used because the ^{23}F and ^{25}F nuclei are radioactive. A quasi-free (p,2p) knockout reaction at intermediate energy was a clean probe. The experiment was done in the RIBF, RIKEN using the BigRPIS and the SHARAQ spectrometer. A primary beam of ^{48}Ca with intensity of 200 pnA and energy of 345*A* MeV bombarded a 30 mm thick ^{9}Be target to create secondary beams of ^{23}F and ^{25}F. The energies of ^{23}F and ^{25}F were 289*A* MeV and 270*A* MeV respectively. Under these energies, the knockout reaction can be treated as a quasi-free proton-proton scattering.

The detector setup around the target is shown in Figure 1. The target was a 114 mg/cm^2 thick solid crystal ($C_{10}H_8$). A carbon target was placed 160 mm downstream for carbon-background estimation. The beam was tracked by two drift chambers (DCX1 and DCX2). The scattered protons were detected using two sets of detectors placed on the left and right sides. Each set of detectors had a

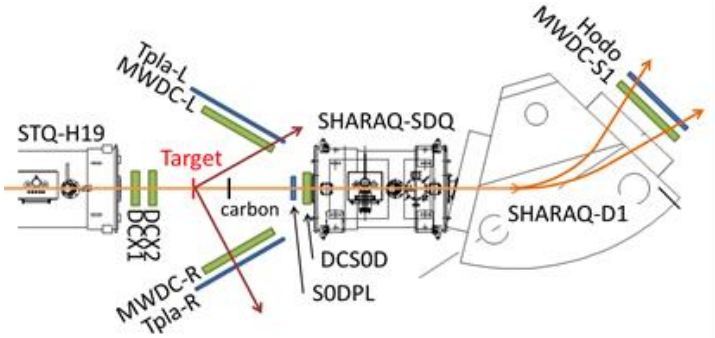

Figure 1 – The layout of the particle detectors around the target. The green boxes are drift chambers. The blue boxes are plastic scintillators. The orange arrow is the beam or residues trajectories. The cerise arrows are the scattered and knock out protons.

multi-wire drift chamber (MWDC) and a trigger plastic scintillator (Tpla). The reaction residues were detected using the downstream detectors of a plastic scintillator (S0DPL), a drift chamber (DCS0D), a multi-wire drift chamber (MWDC-S1), and a plastic hodoscope (Hodo). The trigger condition was the coincidence of both Tpla-L and Tpla-R and the beam.

The missing four-momentum of the reaction residue ^{22}O (or ^{24}O) was reconstructed using the four-momenta of the beam and the scattered protons. The excitation energy of the residue ^{22}O (or ^{24}O) was then deduced using the invariant masses of the ^{23}F (or ^{25}F) nuclei and the scattered protons. The reaction was identified using an upstream particle identification (PID), the proton-proton coincidence, the location of the target crystal, and the residue PID. Because the excitation energy of the residue could above neutron thresholds, different oxygen isotopes were observed and selected. This selection partitioned the excitation-energy spectrum into serval components according to the thresholds. The experimental integrated cross-section was compared with the distorted-wave impulse approximation [3] calculation using Dirac-Cooper global potential [4]. The spectroscopic factors were then deduced after analysis of momentum distribution.

Experimental results

The spectroscopic strengths of the valance proton of ^{23,25}F and other fluorine isotopes were shown in Figure 2 [5] [6] [7] [8]. The partial spectroscopic factors of the $1d_{5/2}$ proton from the (^{23}F,^{22}O) and (^{25}F,^{24}O) partitions are plotted as hollow orange dots. Our result was consistent with the result obtained by M. Thoennessen *et al.* [5]. They used a ^{12}C(^{25}F,^{24}O) reaction at 50.4*A* MeV and reported that the spectroscopic factor of the (^{25}F,^{24}O) channel was 0.5 ± 0.1. This agreed with our result of 0.38 ± 0.14. The full strength of the spectroscopic factor of the $1d_{5/2}$ proton of ^{25}F was 1.06 ± 0.28 and it is plotted as an orange solid dot in Figure 2. The full strength was consistent with that of ^{17,19}F. A result from S. Michimasa *et al.* on ^{23}F using ^{4}He(^{22}O,^{23}F) at 35A MeV is plotted as a brown cross. The spectroscopic strength of the $1d_{5/2}$ orbit of ^{23}F was reported to be 1.1 [6]. Since the result was obtained by subtracting all excited states from γ-spectroscopy, and the experimental setup was not sensitive to the ground state, a large error was expected. The figure shows that the spectroscopic strength of the $1d_{5/2}$ proton of ^{25}F was fragmented while the $1d_{5/2}$ proton is in a "single-particle orbit". The results show that the neutron-shell changed.

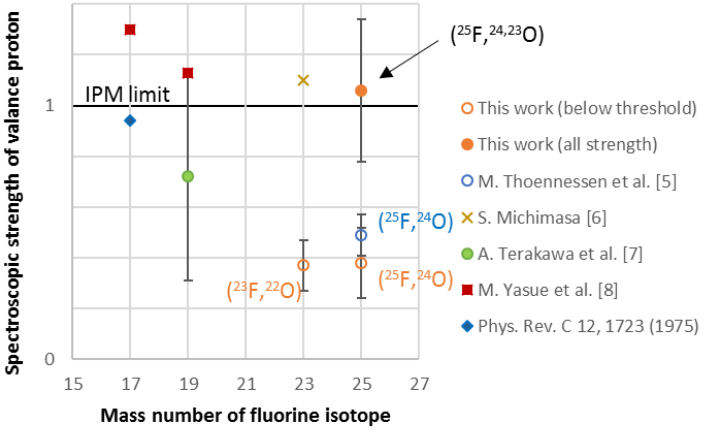

Figure 2 – The spectroscopic strength of the valence proton of the ground state of even-neutron fluorine isotopes [5] [7] [8] [6]. The solid dots represent full strength of the valance proton. The hollow dots represent partial strength of the valance proton. The cross is the result from S. Michimasa [6]. The bracket (^{23}F,^{22}O) refers the selection of ^{22}O from downstream PID.

Discussion

Unified Picture of Fluorine

The fragmentation implies that the wavefunction of ^{23,25}F is expressed as $|{}^{A}\mathrm{F}\rangle = |\pi\rangle \otimes \left(\beta_1 |{}^{A-1}\mathrm{O}_{\mathrm{g.s.}}\rangle + \beta_2 |{}^{A-1}\mathrm{O}^{*}\rangle + \cdots\right)$, where β_i is the square root of the spectroscopic factor, $|\pi\rangle$ is the wavefunction of 1d$_{5/2}$ proton, and $|{}^{A-1}\mathrm{O}\rangle$ are the wavefunctions of oxygen core. The operator $\otimes$ means antisymmetric isospin and spin-isospin coupling. This expression indicates that the single 1d$_{5/2}$ proton changes the neutron sd-shell structure significantly that the fluorine has large component of 1d$_{5/2}$ proton + excited oxygen, i.e. β_2 is large. These excited oxygen components represent large neutron-configuration mixing. That indicates a smaller spacing between 1d$_{5/2}$, 2s$_{1/2}$ and 1d$_{3/2}$ orbits, and the N = 16 magicity disappears. Figure 3 shows the mechanism of the change of the neutron shell by the single 1d$_{5/2}$ proton via tensor force [1]. The tensor force between proton and neutrons lowers the 1d$_{3/2}$ neutron orbit and raises the 1d$_{5/2}$ neutron orbit. The nuclear structures of the ^{25}F and ^{23}F demonstrates the Type-1 shell evolution driven by tensor force [9].

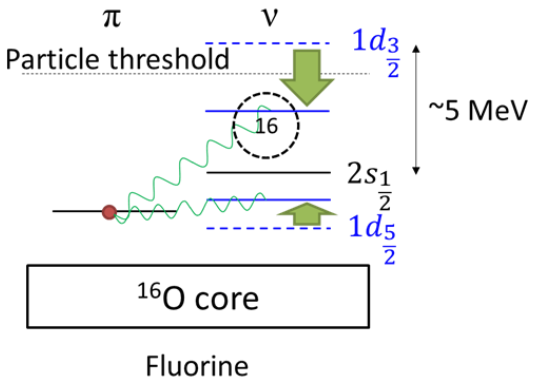

Figure 3 – The mechanism of the change of neutron shell structure by the 1d$_{5/2}$ proton in fluorine. See main text for explanation.

Shell Model Calculation

In order to study the shell structure, the shell model calculations were performed with OXBASH [10] using SFO (in p-sd model space) [11], USDB (in sd model space) [12], and SDPF-MU (in sd-pf model space) [13] interactions. The calculated excitation energy spectra (of SFO interaction) supported the momentum analysis. The total strength of the spectroscopic factor of the 1d$_{5/2}$ proton of the present interactions also agreed with experimental results. However, none of the interaction can reproduce the fragmentation of the spectroscopic strength (Table 1). This indicates the tensor force between the 1d$_{5/2}$ proton and the 1d$_{3/2}$ neutrons should be stronger that the 1d$_{3/2}$ neutron orbit should be lower for larger configuration mixing. A stronger tensor force was imitated by lowering the single particle

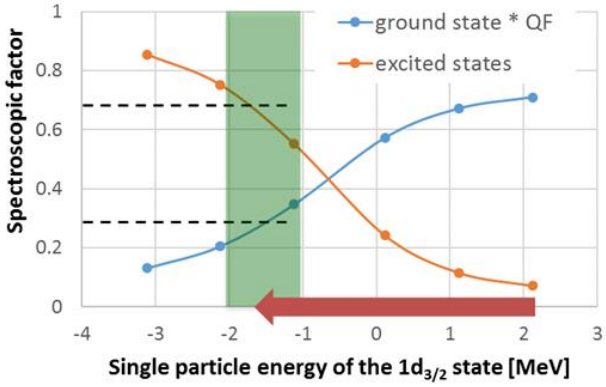

Figure 4 – The spectroscopic factors of the ^{24}O ground state and excited states in a function of the single particle energy of the 1d$_{3/2}$ orbit. The ground-state spectroscopic factor was multiplied by a quenching factor (QF) of 0.7. The experimental SFs of ^{25}F are shows as dashed lines. The red arrow indicates the shift of the single particle energy. The green band highlights the possible energy.

energy of the $1d_{3/2}$ neutron. Figure 4 shows the result based on USDB interaction. The original single particle energy was 2.117 MeV. This toy model suggests the single particle energy of the $1d_{3/2}$ neutron should be lowered by ~3.5 MeV.

Table 1 –Spectroscopic factors of experimental results and shell model calculations.

	Residue	Orbit	S_{exp}	S_{sh}(SFO)	S_{sh}(USDB)	S_{sh}(SDPF-MU)
^{23}F(p,2p)	^{22}O	$1d_{5/2}$	0.37 ± 0.10	0.92	1.08	1.00
	^{21,20}O	$1d_{5/2}$ + p-orbit	4.9 ± 1.5	5.21	-	-
^{25}F(p,2p)	^{24}O	$1d_{5/2}$	0.38 ± 0.14	0.9	1.01	0.95
	^{23}O	$1d_{5/2}$	0.69 ± 0.25	0.1	-	-
	^{22,21}O	$1d_{5/2}$ + p-orbit	4.4 ± 1.6	6.139	-	-

We have to emphasis that our results show that the reduction factors $R_S = S_{exp}/S_{sh}$ for the ^{22}O and ^{24}O residues are ~0.4 and accidentally agreed with the Gade plot [14]. The author claimed that the plot was due to the correlation effect involving the removed nucleon. However, the correlation effect is very small in the $1d_{5/2}$ proton of ^{25}F, and the fragmentation is due to the change of the neutron shell. Also, our results suggest the present shell model interactions are inaccurate, but the Gade plot relied on the correctness of the shell model interactions. This fundamental difference makes the comparison between our result with the Gade plot to be logically invalid.

Conclusion

We aim to know how the neutron shell structure is changed by the $1d_{5/2}$ proton in ^{23,25}F. Using proton knockout spectroscopy, the experimental results implied that the proton modifies the neutron-shell structure significantly, and ^{A}F cannot be expressed as a simple system of a proton on top of the ground state of $^{A-1}$O. The change could be understood qualitatively using Type-I shell evolution driven by tensor force. The discrepancy between the experimental results and the present shell model interactions indicates the strength of the tensor force should be larger.

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