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Study of single-particle states in ^{23}F using proton transfer reaction

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Abstract. The proton shell structure in neutron-rich fluorine ^{23}F was investigated using the in-beam γ-ray spectroscopy technique via the proton transfer reaction onto the unstable nucleus ^{22}O, in addition to α inelastic scattering on ^{23}F, and the neutron-knockout reaction from ^{24}F. The level and γ-decay scheme in ^{23}F was deduced from de-excitation γ-ray–particle coincidence events. We found that a single-particle state at 4.061 MeV has a large contribution from the d shell by the analysis of population strengths and the angular distribution for the state. We reported here the present experiment and the preliminary results.

PACS. 21.10.Pc Single-particle levels and strength functions – 23.20.Lv γ transitions and level energies – 25.55.Hp Transfer reactions – 27.30.+t $20 \leq A \leq 38$

1 Introduction

Nuclear shell structure is mainly interpreted by single-particle motion in a mean-field including a spin-orbit potential. Recent findings of the disappearance of magic numbers and/or of new magic numbers in neutron-rich nuclei may indicate that the mean-field changes as a function of neutron number. In this respect, neutron-rich fluorine isotopes are interesting because they are the nuclei between the new magic number of $N = 16$ [1] and the island of inversion [2].

So far, nuclear structure physics in neutron-rich nuclei, including fluorine isotopes, mainly proceeds by focusing on neutron orbitals. However, protons composing a nucleus are strongly affected by neutrons through proton-neutron interactions, and vice versa. Therefore, studies of proton orbitals in neutron-rich nuclei are also essential for understanding these structures; proton orbitals may change irregularly due to shell evolution in neutron-rich regions. Thus, we studied proton nuclear structure in neutron-rich fluorine ^{23}F using in-beam γ-ray spectroscopy by a one-proton transfer reaction.

Proton transfer reactions are well known to be a good probe to investigate proton orbitals in a nucleus, and many one-proton stripping reactions have been used for studying single-particle nature, *e.g.*, (d, n) and (α, t). In the present experiment, we selected the α-induced one-proton transfer reaction (α, t). In this case, a proton is transferred onto the unstable nucleus ^{22}O, thus it is important for a transfer reaction to match well with secondary beam conditions. With respect to beam intensity, intermediate-energy fragmentation reactions are useful in production of secondary beam. The beam energy is typically at 30–50 A MeV and somewhat higher for (d, n) reactions. However, the cross section for the (α, t) reaction has a maximum (on the order of mb) in this energy region, and it is expected to be larger than those of the (d, n) reaction. The reason is naively considered to be why a proton is picked up on the Fermi surface of an α particle which is deeply bound and has high-momentum components. As another merit, intermediate-energy fragmentation reactions enabled us to measure simultaneously some of other reactions for investigating ^{23}F, because the secondary beam was a cocktail of some nuclei in vicinity of ^{23}F. In the present configuration, we additionally observed α inelastic scattering of ^{23}F

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Table 1. Composition of the secondary beam.

Nuclide	^{22}O	^{23}F	^{24}F
Energy [A MeV]	35	41.5	36
Momentum acceptance	4%	4%	4%
Intensity [particle/s]	2×10^3	6×10^2	3×10^2
Flux percentage	42.0%	12.8%	6.9%
Measurement		3 days	

and neutron-knockout reaction from ^{24}F. A comparison of population strengths from all of these reactions is effective in deducing the single-particle nature of excited states.

2 Experiment

We simultaneously measured de-excitation γ rays from three different reactions aiming at excited states in ^{23}F: proton transfer reaction onto ^{22}O, α inelastic scattering on ^{23}F and neutron-knockout reaction from ^{24}F. The experiment was performed at the secondary beam line in RIKEN Accelerator Research Facility. The secondary beam, including ^{22}O, ^{23}F and ^{24}F, was produced by projectile fragmentation reactions of 63-MeV/nucleon ^{40}Ar beam impinging on a ^{9}Be target of 180-mg/cm^2 thickness. Fragments were analyzed by the RIPS separator [3] using a wedge aluminum degrader of 321 mg/cm^2 thickness at the first dispersive focal plane, where the momentum acceptance was set to be 4%. Secondary beam particles were identified event-by-event by energy losses in a silicon detector and time-of-flight between two plastic scintillators set 5 meters apart. The averaged intensities and mean energies of components in the cocktail beam are listed in table 1.

The secondary beam bombarded a liquid-helium target [4] of 100 mg/cm^2, which was contained in an aluminum cell with two windows of 6-μm havar foils. The window size was 30 mm diameter. The helium was condensed by a cryogenic system, and kept at around 4 K through the experiment.

Reaction products were detected by a ΔE-E telescope located at the end of the beam line, and were identified by the method of time-of-flight (TOF), energy loss (ΔE), and energy (E). The telescope consists of 9 silicon detectors for ΔE arranged in a 3×3 matrix, and 36 NaI(Tl) detectors [5] for E arranged in a 6×6 matrix. The angular acceptance of the telescope was in 0–6 degrees in laboratory system. TOF was measured between the secondary target and NaI(Tl) scintillators. In the present experiment, the resolutions for atomic and mass numbers in fluorine isotopes were 0.18 (σ) and 0.35 (σ), respectively.

Scattering angles of the reaction products were measured by three parallel-plate avalanche counters (PPACs) [6]. The two PPACs, with effective areas of 100×100 mm^2, were placed before the secondary target to determine the direction and the hit point of the beam. The other PPAC, with an effective area of 150×150 mm^2, was placed after the target to measure the direction of the reaction products. Their position resolutions were about 1 mm and the resolution of the scattering angles were estimated to be 0.25 degrees (σ) in laboratory flame.

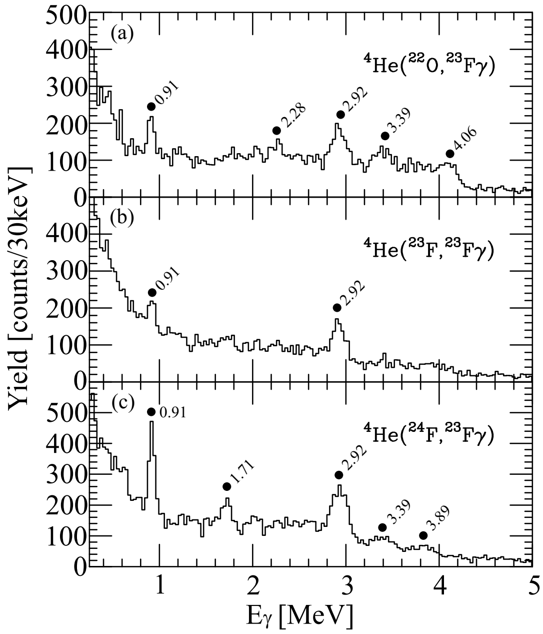

Fig. 1. Gamma-ray spectra from three different reactions: (a) proton transfer reaction ^{4}He(^{22}O,^{23}Fγ), (b) inelastic scattering ^{4}He(^{23}F,^{23}Fγ), and (c) neutron-knockout reaction ^{4}He(^{24}F,^{23}Fγ).

For de-excitation γ-ray detection from the reaction products, we used the DALI(II) [7] NaI(Tl) detector array. The array consisted of 150 NaI(Tl) scintillators and surrounded the secondary target in the angular range of 20–160 degrees with respect to the beam axis. The entire system was composed of 13 layers, and was designed for γ-ray detection from nuclei moving with high velocity. In the present experiment, the full-energy-peak efficiency was 17.6% for 1.33-MeV γ rays from ^{60}Co, and the energy resolution, including Doppler-shift corrections, was 8.2% (σ) for the de-excitation γ rays at 3.2 MeV from ^{22}O moving with $\beta \sim 0.27$.

3 Analysis outline

We obtained remarkably different γ-ray spectra in ^{23}F from the proton transfer ^{4}He(^{22}O,^{23}F), the inelastic scattering ^{4}He(^{23}F,^{23}F), and the neutron-knockout ^{4}He(^{24}F,^{23}F) reactions as shown in fig. 1. We observed de-excitation γ rays at 0.9 and 2.9 MeV in all reactions, whereas the other γ rays observed were reaction-dependent. This difference was considered to be derived from populating different excited states by these reactions.

In order to deduce a scheme of excited states in ^{23}F, we examined coincidences of multiple γ rays in the three reactions. The energies of excited states in ^{23}F were determined by total energies of sequential γ decays. In the present analysis, each sequential γ decay was identified by the evidence that a yield of the coincident event was

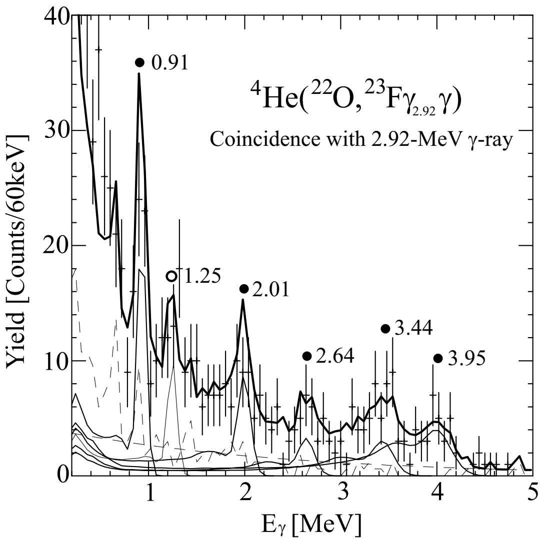

Fig. 2. Gamma-ray spectrum from the transfer reaction ^{4}He(^{22}O,^{23}F) in coincidence with the 2.92-MeV γ ray. The thin solid curves show response functions of the γ-ray detectors array for each of γ lines, which were calculated by Monte-Carlo simulation, and the dashed curves show contaminated events from ^{22}F and the exponential background. The thick solid curve shows the summation of these thin solid and dashed curves. In the figure, we identified five γ lines coincident with the 2.92-MeV γ ray pointed by closed circles, whereas the γ line with an open circle was found to correspond to the sequential γ decay of the 3.39-MeV and 1.25-MeV lines.

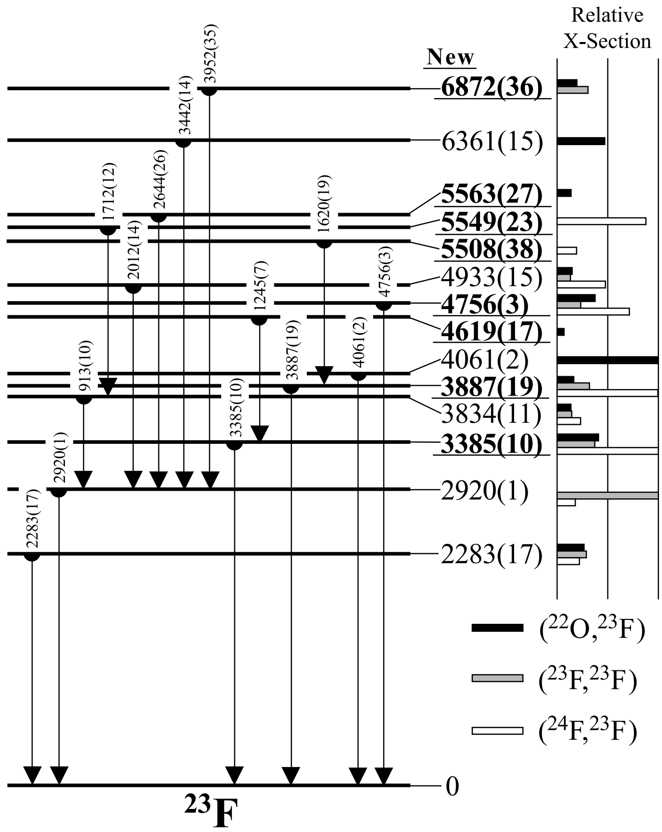

Fig. 3. Tentative level and γ-decay scheme in ^{23}F. Level energies with underlines show newly observed excited levels in the present experiment. Shown errors with γ ray and excited energies are statistical errors obtained by fittings of γ-ray spectra with simulated response functions of DALI(II). The bars in the right side of excitation energies show relative cross sections to populate these states.

consistent with yields of the members within the precision of the statistical error.

Figure 2 shows the γ-ray spectrum obtained from the transfer reaction in coincidence with the 2.92-MeV γ ray. So far, two previous works were performed to investigate excited states in ^{23}F: Orr *et al.* [8] has reported six excited states at 2310(80), 2930(80), 4050(50), 5000(60), 6250(80), and 8180(110) keV in ^{23}F; Belleguic *et al.* [9] has reportedly observed two γ rays at 2900 keV and 910 keV from ^{23}F. The first one corresponded to the decay from the 2900-keV state to the ground state, whereas the second one corresponded to the decay from the 3810-keV state to the 2900-keV state. The present result was consistent with the previous results as we observed the coincidence events of the 2.92-MeV and the 0.91-MeV γ rays. We identified, moreover, the coincidental γ rays at 2.01, 2.64, 3.44 and 3.95 MeV shown with closed circles in fig. 2. These γ rays were found to correspond to the decays from higher excited states to the 2.92-MeV states. The 1.25-MeV γ ray shown with a open circle in fig. 2 was, however, found to be sequential with the 3.39-MeV γ decay by the analysis of plural γ-detection events in coincidence with the 3.39-MeV γ ray. This false peak came from 1.25-MeV photons in coincidence with the Compton events of the 3.39-MeV line.

We examined possible coincidences of multiple γ rays in the three reactions as the above-mentioned case and preliminarily reconstructed the γ-decay scheme in ^{23}F. The placement of γ rays was determined by requiring that the weaker one was located on the top of the stronger one.

4 Results and discussion

Figure 3 shows the proposed level scheme in ^{23}F deduced from the three reactions. Many of the excited states shown in the figure were commonly observed from the three reactions, and the level scheme greatly agrees with the previous results. We reconfirmed the six excited states shown with roman style, and found eight excited states at 3385(10), 3887(19), 4619(17), 4756(3), 5508(38), 5549(23), 5563(27) and 6872(36) keV for the first time, which are shown with underlined bold style. Here, numbers in parentheses show the statistical errors deduced from fitting with simulated response functions of the γ-ray detectors array.

In fig. 3, the bar graph on the right side of the excitation energies shows the relative cross sections to populate the excited states. In these relative cross sections, one can see that the 4.06-MeV state was strongly populated by the proton transfer reaction, but hardly at all by the other reactions. Such differences of population strengths

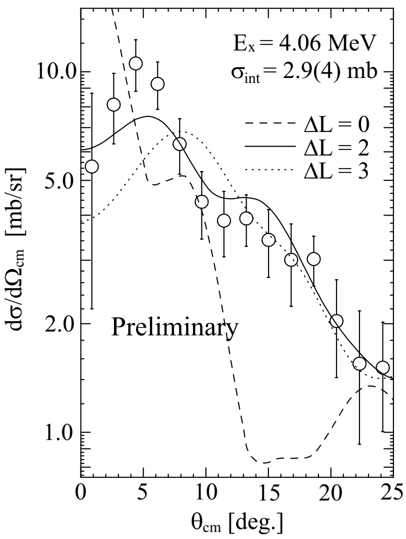

Fig. 4. Angular distribution for the 4.061-MeV state from the proton transfer reaction. Curves in the figure show the predictions obtained from DWBA calculations. Dashed, solid and dotted curves correspond to transferred orbital angular momenta $\ell = 0$, 2 and 3, respectively. The optical potential parameters used are described in the text.

are naively considered to reflect the matching between the reaction channel and the property of excited states. In the present experiment, the three kinds of reactions are considered to populate different states as follows: The transfer reaction mainly populates proton single-particle states; The α inelastic scattering makes core excitations and possibly populates single-particle states through non spin-flip excitation; and the neutron-knockout reaction populates neutron-hole states. Therefore, the difference of population strengths among these reactions is significant to estimate the properties of the excited state. Concerning the 4.06-MeV state, this strongly suggests that the state has the single-particle nature and is excited from the ground state through a spin-flip process.

Figure 4 shows the angular distribution of outgoing ^{23}F for the 4.061-MeV state together with predictions calculated by distorted-wave Born approximation (DWBA) to transfer a proton into the s, d and f orbitals. Optical potentials used in the initial and final channel were determined by angular distributions of α inelastic scattering for the first 2^+ state in ^{22}O, and for the 2.92-MeV state in ^{23}F, respectively. The measured angular distribution was found to agree with the $\ell = 2$ transition. The 4.061-MeV state, therefore, is preliminarily assigned to have $J^\pi = 3/2^+$ or $5/2^+$. The previous works [8,10,11] reported the ground state in ^{23}F to have $5/2^+$. Therefore, the state at 4.061 MeV is considered reasonably to have $3/2^+$ as a proton single-particle state in the $d_{3/2}$.

5 Summary

We investigated the proton shell structure in neutron-rich ^{23}F by in-beam γ-ray spectroscopy from the proton transfer reaction corresponding with inverse kinematics of (α, t). Moreover we studied the excited states in ^{23}F through the α inelastic scattering on ^{23}F and the neutron-knockout reaction from ^{24}F. The level and γ-decay scheme in ^{23}F was deduced from de-excitation γ rays and these coincidence data obtained from the three reactions. From this study, we reconfirmed the previous results and found eight excited states. Furthermore the 4.061-MeV state was found to have single-particle nature and reasonably considered to have $J^\pi = 3/2^+$.

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