First observation of an isomeric state in proton drip-line nucleus ^{26}P

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Abstract. An isomeric state in the proton drip-line nucleus ^{26}P has been observed by the γ-ray spectroscopy. The γ-ray energy and the half-life are 164.4 ± 0.1 keV and 120 ± 9 ns, respectively. For the isomeric transition of the mirror nucleus ^{26}Na, the γ-ray energy of 82.40 ± 0.04 keV and the half-life of 4.35 ± 0.16 μs are also revised. Comparing the experimental reduced transition probabilities of ^{26}Na and ^{26}P with theoretical ones calculated by the shell model with the USDA interaction, the spin-parity (J^π) of the isomeric state in ^{26}P is most likely to be 1^+.

1 Introduction

The proton drip-line nucleus ^{26}P has attracted much interests since it is a candidate of proton halo nucleus due to the possible weakly-bound valence proton in $1s_{1/2}$ state [1]. Furthermore, it is a key nucleus of the astrophysical problems such as the rp-process nucleosynthesis and X-ray bursts [2, 3]. These studies are strongly related to the proton separation energy (S_p) *i.e.* the mass and the Q value of proton decay. The mass prediction from Audi *et al.* gives the atomic mass excess of ^{26}P, $\Delta(^{26}\text{P}) = 10970 \pm 200$ keV (*i.e.* $S_p = 144 \pm 200$ keV) [4]. In the β-decay experiment [5], Thomas *et al.* deduced $S_p = 0 \pm 90$ keV by using the Coulomb energy difference from ^{26}Si and the semi-empirical Isobaric multiplet mass equation (IMME) prediction [6]. On the other hand, the mirror nucleus ^{26}Na has a low-lying isomeric state at the excitation energy of 82.5 ± 0.5 keV [7]. The spin-parity (J^π) and the half-life of the isomeric state are determined to be 1^+ and 9 ± 2 μs, respectively. Assuming the mirror symmetry, there should be an isomeric state with $J^\pi = 1^+$ at the small excitation energies
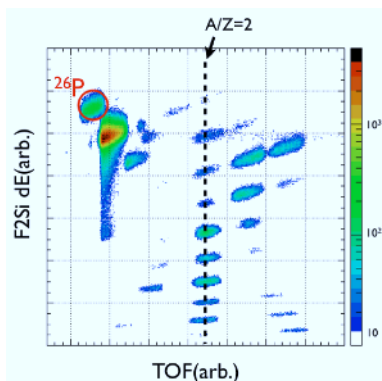
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Figure 1. The particle identification plot via $B\rho$-TOF-ΔE method.

Figure 2. The γ-ray detection system.
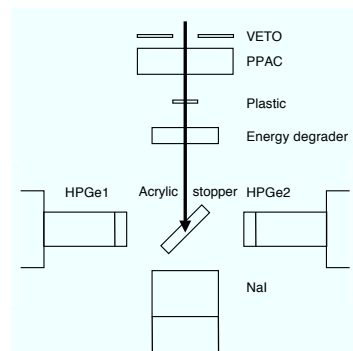
in ^{26}P. In this case, the isomeric state can also be the candidate of the proton halo nucleus and is strongly related to the astrophysical problems. However, if the excitation energy of the mirror state is much larger than S_p, it can decay by the fast direct proton emission. To investigate the existence of the isomeric state in ^{26}P, the γ-ray spectroscopy has been carried out at NIRS (National Institute of Radiological Sciences)-HIMAC. Additionally, the excitation energy and the half-life of the isomeric state in ^{26}Na were precisely measured to discuss the isospin symmetry of transition probabilities.

2 Experiment

A primary beam of ^{28}Si with an energy of 300 MeV/u and with an intensity of 2×10^8 particles per spill (pps) was accelerated by the heavy-ion synchrotron at NIRS-HIMAC. Duration of each beam spill was 1 sec and the repetition time was 3.3 sec. Secondary beams of neutron-deficient nuclei were produced by bombarding a 1.9-g/cm^2-thick polyethylene target. They were separated and identified by passing through the secondary beam line (SB2) consisting of two dipole magnets and a 3.4-g/cm^2-thick wedge-type Al degrader placed at the first focal plane (F1) between these magnets [8]. The particle identification (PID) was performed by $B\rho$-TOF-ΔE method. Figure 1 shows the PID plot with the time of flight (TOF) vs. the energy loss (ΔE). The TOF was measured by using two 0.5-mm-thick plastic scintillators at F1 and the third focal plane (F3) which were 24 m apart along the beam line. The ΔE was measured by a 0.5-mm-thick Si detector placed at the second focal plane (F2) after the second magnet. The yield of ^{26}P was 30 pps and the purity was 4%, where the main contamination was ^{25}Si. After passing through the SB2, the 100-MeV/u ^{26}P beam was transported to the γ-ray detection system at the third focal plane. The schematic drawing of the system is shown in Fig.2. The beam penetrated through a plastic scintillator with a 20-mmϕ hole (VETO), a parallel plate avalanche counter (PPAC) with an effective size of 100×100 mm^2, the plastic scintillator providing the stop signal for the TOF, and a 1.3-g/cm^2-thick carbon energy degrader. Finally, the beam was implanted in the center of a 0.6-g/cm^2-thick acrylic stopper. The acrylic stopper was tilted by 45 degrees with respect to the beam axis. The γ rays emitted by the implanted nuclei were measured by two high-purity germanium (HPGe) detectors with 0.5-mm-thick Be windows. The HPGe detectors
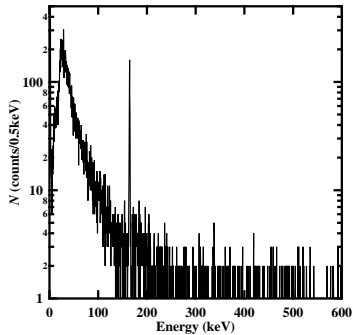
Figure 3. The γ-ray energy spectrum obtained in coincidence with the incoming signal of ^{26}P with a time gate of 2 μs.
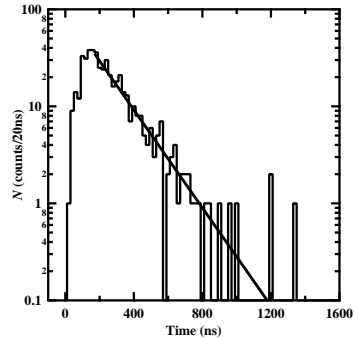
Figure 4. The time spectrum gated on the 164-keV peak. The solid line represents the fitting result.

were set on both sides of the stopper and were placed perpendicular to the beam axis. The distances between both of the HPGe detectors and the stopper were 50 mm. Figure 3 shows the γ-ray energy spectrum obtained in coincidence with the incoming signal of ^{26}P with a time gate of 2 μs. A peak at 164.4 ± 0.1 keV was clearly observed. Any other peaks associated with ^{26}P were not observed in our experiment. The 164-keV peak disappeared in anti-coincidence with the signal of ^{26}P. The time spectrum gated on the 164-keV peak is shown in Fig.4. The half-life of 120 ± 9 ns was determined by fitting the decay curve using the maximum likelihood method. The isomeric ratio after stopping in the acrylic stopper was determined to be 32 ± 3%, where the total absolute detection efficiencies for two HPGe detectors at 164 keV were deduced to be 1.6% by using a checking source of ^{133}Ba. Taking into account the inflight decay, the isomeric ratio at the production target was deduced to be 97^{+3}_{-10}%. This fact means that the branching ratio of the direct proton decay is at most 3^{+10}_{-3}%, even if the isomeric ratio at the production is 100%.

As is the case for ^{26}Na, the isomeric γ rays were observed in the similar set up. A peak at 82.40 ± 0.04 keV was observed. The half-life of 4.35 ± 0.16 μs was determined by fitting the decay curve. The present result of the half-life is not so inconsistent with the previous result of 9 ± 2 μs, because the error of the previous value is very large.

3 Discussion

The observed 164-keV γ rays for ^{26}P are not following the direct proton decay, because there are no excited states emitting the γ rays with the same energy in ^{25}Si. Therefore, it is concluded that the 164-keV γ rays are originated from an isomeric state in ^{26}P. Since other statistically significant peaks were not observed in this experiment, the γ rays are possible to be emitted from the first excited state with an excitation energy of 164.4 keV to the g.s. in ^{26}P. It is also concluded that the isomeric state is below or not much higher than S_p (*i.e.* proton decay threshold), because the branching ratio of the direct proton decay is nearly equal to zero. This is consistent with the results of S_p = 144 ± 200 keV by Audi *et al.* and S_p = 0 ± 90 keV by Thomas *et al.*. The reduced transition probabilities for the isomeric state in ^{26}P can be evaluated in Weisskopf unit (W. u.) by using the observed excitation

Table 1. Transition strengths for different multipolarity assumptions for 164-keV γ decay in ^{26}P.

	$L = 1$	$L = 2$	$L = 3$	$L = 4$	$L = 5$
Electric (W.u.)	1.44×10^{-6}	8.58×10^{0}	7.75×10^{7}	1.04×10^{15}	1.95×10^{22}
Magnetic (W.u.)	4.13×10^{-5}	1.89×10^{4}	1.32×10^{13}	1.36×10^{22}	1.96×10^{31}

Table 2. The experimental and theoretical B(E2) values of ^{26}P and ^{26}Na in units of e^2fm^4.

Nuclide	This work	Ref. [7]	Shell model calc.
^{26}P	39 $\pm$ 3	-	37.0
^{26}Na	30.0 $\pm$ 0.7	16^{+5}_{-3}	41.9

energy and the half-life. These values are summarized in Table 1, where the branching ratio of the proton decay and electron conversion are tentatively assumed to be zero. Since the reduced transition probability in units of W. u. should not be extremely large, the multipolarities of E1, E2, and M1 are possible. Excluding the E1 and M1 transitions that show somewhat too much hinderance, the most probable transition type is E2. Assuming the transition type of pure E2 to the g.s. with $J^{\pi} = 3^{+}$ since an admixture of M1 would drastically increase the transition rate, it is expected that the isomeric state in ^{26}P has $J^{\pi} = 1^{+}$ or $J^{\pi} = 5^{+}$. The shell model calculation using the USDA interaction [10] suggests that there are the first 1^{+} state at 80 keV and the first 5^{+} state at 2240 keV in ^{26}P. Since the excitation energy of the isomeric state is similar to that of 1^{+} state in the shell model calculation, it is probable that the isomeric state in ^{26}P has $J^{\pi} = 1^{+}$.

Experimental and theoretical E2 transition probabilities B(E2) for ^{26}Na and ^{26}P are summarized in Table 2. In the deduction of experimental values, 10%(1.6%) for ^{26}Na(^{26}P) of the internal conversion coefficient were taken into account by using Kibédi's calculation [9]. In the shell model calculation, the effective charges for proton and neutron, $e_p = 1.3e$ and $e_n = 0.5e$, are used. The theoretical B(E2) values well reproduces the present experimental B(E2) values.

Acknowledgments

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