Momentum dependence of spin polarization for beta emitting nuclei produced through charge exchange reaction at intermediate energy

S. Momota1, M. Mihara2, D. Nishimura3, M. Fukuda2, Y. Kamisho2, M. Wakabayashi2, K. Matsuta2, S. Suzuki4, M. Nagashima4, Shengyun Zhu5, Daqing Yuan5, Yongnan Zheng5, Zuo Yi5, Ping Fan5, T. Izumikawa6, A. Kitagawa7, S. Sato7, M. Kanazawa7, M. Torikoshi7, T. Minamisono2, Y. Nakamura4, K. Tashiro4, A. Honma4, N. Yoshida8, H. Shirai8, T. Ohtsubo4, T. Nagatomo9, H. Uenishi2, K. Iwamoto2, M. Yaguchi2, T. Ogura4, T. Ito4, K. Yamamura10, Y. Ichikawa8, Y. Nojiri1, J. R. Alonso11, and T.J.M. Symons11

1Kochi Univ. of Tech., Kochi 782-8502, Japan

2 Osaka Univ., Osaka 560-0043, Japan

3 RIKEN, Saitama 351-0198, Japan

4 Niigata Univ., Niigata 951-2181, Japan

5 CIAE, Beijing 102413, People's Republic of China,

6 RI Center, Niigata Univ., Niigata 951-8510, Japan

7 NIRS, Inage, Chiba 263-8555, Japan,

8 TIT, 2-12-1, Tokyo 152-8550, Japan,

9 J-PARC, Ibaraki 319-1195, Japan,

10 Fukui Univ. of Tech., Fukui 910-8505, Japan,

11 LBL, Berkeley, CA 94720, USA

momota.sadao@kochi-tech.ac.jp

Abstract In order to investigate the polarization process in charge exchange reactions, we observed the momentum and angular distribution as well as nuclear polarization of a proton-rich beta-emitting nucleus, ^{28}P (I^{π}=3^{+}, $T_{1/2}$ = 270 msec), produced through the reaction ^{28}Si+^{9}Be at E=100 MeV/u, by selecting the momentum and the ejection angle. An analysis by using double Gaussian functions resolved the observed momentum distribution into two reaction components, nucleon knockout and pick-up abrasion reactions, suggested in a previous study. The behavior of the observed angular distribution and nuclear polarization implies the influence of those two components. The momentum dependence of the observed nuclear polarization of ^{28}P could be consistently reproduced by a simple model, in which two reaction components are considered. The present study also shows that the charge exchange reaction at intermediate energy is a useful method to produce polarized beta-emitting nuclei, especially for proton-rich nuclei.

Keywords Production of nuclear polarization, Beta emitting nuclei, Nuclear moments

1 Introduction

A spin polarized beta-emitting nucleus is one of the useful probes to investigate nuclear structures by means of nuclear moments and weak interactions. By using nuclear polarization and precisely determined nuclear moments of beta-emitting nuclei, hyperfine interactions can be efficiently examined. As a polarization method, a projectile fragmentation process at intermediate energy was investigated [1], and has been popularly applied to study nuclear physics and material science. In the case of proton rich nuclei, contaminated isotones, which cannot be easily separated from objective nuclei by means of fragment separator, usually causes a reduction in the observed asymmetry of beta-ray emission. Recently, our group observed the nuclear polarization of beta-emitting nuclei, which were produced through a charge exchange reaction [2], [3]. In the present study, the polarization phenomenon was examined based on experimental results for ^{28}P.

2. Experimental

The present experiment was performed at NIRS (National Institute of Radiological Sciences). A beta-emitting nucleus, ^{28}P (I^{π}=3^{+}, $T_{1/2}$ = 270 msec), was produced through a charge exchange reaction by bombarding a 2-mm thick Be-target with a primary beam of ^{28}Si at E=100 MeV/u, provided by HIMAC synchrotron accelerator. The produced ^{28}P was separated and identified with a high-energy transport system, SB2, used as a doubly achromatic spectrometer. The momentum and the angular distribution of ^{28}P were observed with the spectrometer. The momentum acceptance of the spectrometer was adjusted to $\Delta P/P$ =±0.5 (±1.0) % for measurements of the momentum (angular) distribution. The angular acceptance was adjusted to ±0.6 deg. in both θ_x and θ_y for measurements of the momentum and angular distributions. The angular distribution was observed at rigidity ($B\rho$) values of 96.5, 97.5, and 98.5% of that corresponding to the beam velocity. In order to observe the nuclear polarization (P_{I}) of ^{28}P, the momentum acceptance of the spectrometer was adjusted to $\Delta P/P$ =±1.0%, and the angular acceptance was adjusted to ±0.6 deg. in both θ_x and θ_y. The ejection angles of 1.2, 1.0 and 0.7 deg. were selected at $B\rho$ = 96.5, 97.5 and 98.5%, respectively. The ejection angle was so determined that the production rate of ^{28}P became half of that observed at the forward angle. The selected ^{28}P was slowed down and implanted in a catcher of Pt foil, typically cooled down to 20 K, and placed under a strong magnetic field of 1.2 T, to preserve P_{I}.

An asymmetry in the beta-ray emission of polarized ^{28}P was observed by a pair of plastic-scintillation-counter telescopes, and P_I was detected as the asymmetry change induced by means of the NMR technique. According to particle identification observed by the spectrometer, the main beta-ray contamination was ^{27}Si ($T_{1/2}$ = 4.16 sec). Considering a larger Q_β of ^{28}P (14.33 MeV) compared with that of ^{27}Si (4.81 MeV), a 1.0 mm-thick Al plate was used as a beta-absorber in the beta-ray telescopes to reduce the contribution of ^{27}Si. In order to monitor the contamination of ^{27}Si, the time spectrum of beta-ray counting was simultaneously observed in P_I measurements.

3. Results and discussion

^{28}P was contaminated by ^{27}Si, which is one of the isotones of ^{28}P, as shown in Fig. 1. Compared with the projectile fragmentation process, a larger deceleration of the center momentum from that corresponds to the primary beam velocity (~ -1.5%) was observed, as shown in Fig. 1. This large deceleration effect is expected to be an advantage to apply a charge exchange reaction to reduce the contamination by ^{27}Si compared with the fragmentation process. The typical angular distribution of ^{28}P is shown along with the fitting results by the integrated Gaussian function in Fig. 2. The dispersion of the transverse momentum (σ_T) was calculated from the dispersion of the angular distribution.

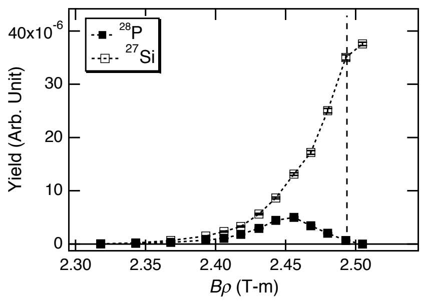

Fig. 1 $B\rho$ distributions of ^{28}P and ^{27}Si. $B\rho$ is the rigidity, which is defined by the spectrometer. The dashed line in the figure indicates the rigidity of ^{28}P with the beam velocity.

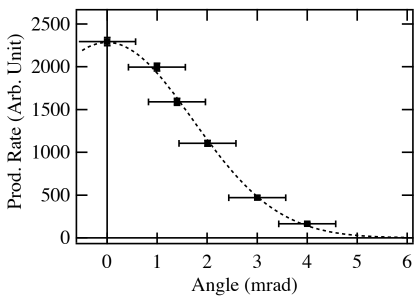

Fig. 2 Typical angular distribution of ^{28}P. The dashed line indicates the fitting result by the integrated Gaussian function.

Fig 3(a) shows the momentum distribution of ^{28}P, provided from the $B\rho$ distribution (Fig. 1). The distribution consists a primary peak, whose center shifts downward by about 200 MeV/c, and a tail component exists at lower momentum. Fig. 3(b) shows the σ_T of ^{28}P, provided from the analysis of the angular distribution, as a function of the momentum. Fig. 3(b) shows that the tail component in Fig. 3(a) has a larger σ_T compared with that for the primary peak component.

In order to resolve the two components in the momentum distribution, the observed momentum distribution was analyzed by double Gaussian functions. As shown in Fig. 4, the fitting result well reproduces the observed distribution, and provides the center and the dispersion of two components. According to the analysis, the tail component is recognized as the secondary peak, whose dispersion is larger than that of the primary peak. Considering the thickness of the Be-target, the intrinsic width of the primary peak component is significantly narrower than the fitting result (76±1 MeV/c). Therefore, the primary peak would correspond to the nucleon knockout reaction. Considering a larger deceleration and larger dispersion of the longitudinal (139±5 MeV/c) and transverse momentum, the secondary peak component would correspond to the pick-up abrasion reaction.

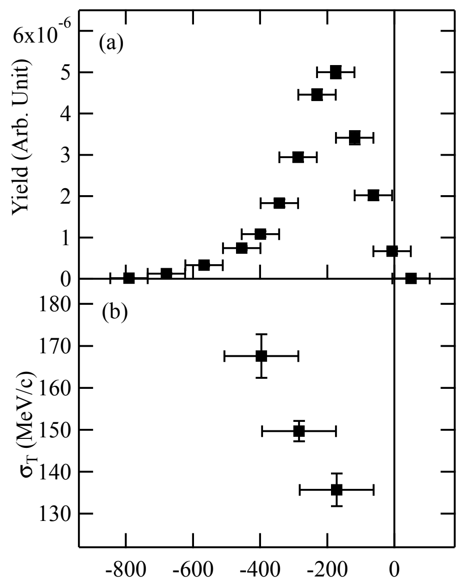

Fig. 3 (a) Momentum distribution and (b) dispersion of the transverse momentum distribution (σ_T) of ^{28}P. dP denotes the momentum shift of ^{28}P from that corresponding to the primary beam velocity.

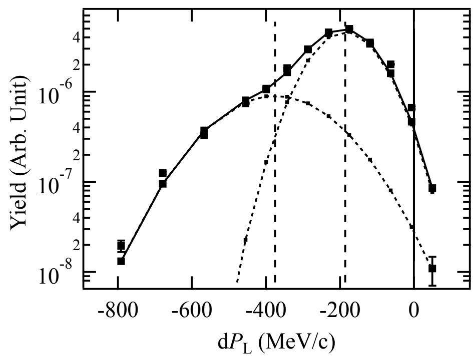

Fig. 4 Momentum distribution of ^{28}P analyzed by double Gaussian functions. The dotted lines show fitting results of two components, and the solid line shows their sum. The dashed line indicates the center of the distribution for each component.

Fig. 5 shows the typical beta-ray time spectrum observed in the P_I measurement. The contamination of ^{27}Si is evaluated from the time spectrum. In order to provide P_I, the asymmetry parameter, A=0.793, and the contamination of ^{27}Si, evaluated from the beta-ray time spectrum, are considered. As shown in Fig. 6, the observed P_I of ^{28}P shows remarkable momentum dependence. According to experimental results of the momentum and the angular distribution, this behavior of P_I would be explained by two reaction channels, which correspond to the primary and the secondary peak components. Assuming a simple model, where P_I can be formulated as

$$P_{\mathrm{I}} = P_1 n_1 + P_2 n_2 , \qquad (1)$$

where P_i and n_i denote the nuclear polarization and the normalized mixing ratio of the i-th peak component, the momentum dependence of P_{I} was analyzed. Applying n_i, which is provided from the fitting results of the momentum distribution, the P_i 's were determined to reproduce the observed P_{I}. This simple analysis gives good agreement with the observed result, as shown in Fig. 6, and the optimized P_i's are determined to be 0.19 ± 0.26 % and 4.48 ± 0.88 % for the primary and secondary peak component, respectively.

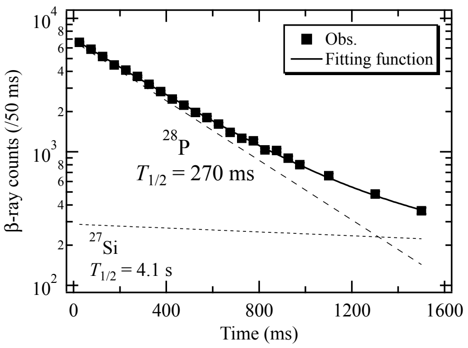

Fig. 5 Typical beta-ray time spectrum observed in the P_{I} measurement.

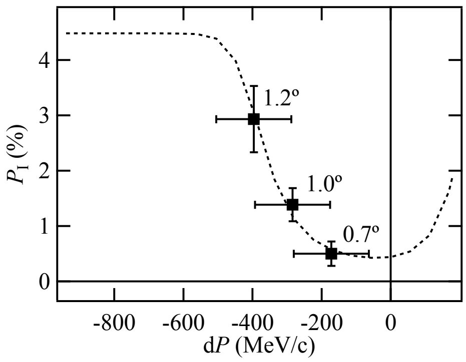

Fig. 6. Observed P_{I} of ^{28}P. The dotted line indicates the fitting result by using a fitting function (1). The angles denoted in the figure indicate the ejection angle selected for the P_{I} measurement.

According to the above analysis, it is implied that the nucleon knockout reaction produces remarkably small nuclear polarization. In our previous study [3], P_{I} of ^{28}P, which was produced through a charge exchange reaction with a CH_2 target, was smaller than that produced with a Be-target. The primary peak component in the momentum distribution of ^{28}P produced with a CH_2 target is significantly dominant; these results are consistent with the present result. On the other hand, our group observed a larger P_{I} of ^{12}C (5~10%), which was produced through a charge exchange reaction with a CH_2 target [4]. In addition, an ambiguity in the present analysis of observed P_{I} remains because of a pragmatic selection of the momentum and the ejection angle of ^{28}P. For comprehensive understanding of the nuclear polarization effect in the charge exchange reaction, further investigations are necessary.

Acknowledgements The present work was performed at NIRS (National Institute of Radiological Sciences)-HIMAC under the research project with heavy ions (program No. P026).

The authors are grateful to the staffs of HIMAC. The work was supported by National Natural Science Foundation of China under the Grant Nos.10975189 and 91126002.

[1] Asahi, K., et al. : Phys. Lett. B 251 (1990) 488-492.
[2] Ohtsubo, T., et al. : Hyperfine. Interact. 180 (2007) 85-89.
[3] Matsuta, K., et al. : Hyperfine. Interact. 198 (2010) 147-151.
[4] Mihara, M., et al., : to be submitted to Hyperfine. Interact.