Nuclear structure of proton-rich unstable nucleus ^{28}P studied by *g*-factor measurement*

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Abstract Nuclear structure of proton-rich unstable nucleus ^{28}P has been studied by measuring its *g*-factor for the first time. The *g*-factor of ^{28}P ($I^{\pi}=3^{+}$, $T_{1/2}$=270.3 ms) was measured by means of β-NMR technique combined with the new polarization technique for charge exchange reaction product in the intermediate energy heavy ion collisions. The obtained *g*-factor of g=0.1028(27) is very much quenched from the Schmidt value, but is well reproduced by the shell model (+0.102). In connection with the magnetic moment of the mirror partner and the β-ray transition probability, the orbital angular momenta and intrinsic spins of protons and neutrons have been determined as $\langle l_{\rm p}\rangle=0.43(29)$, $\langle l_{\rm n}\rangle=1.85(29)$, $\langle S_{\rm p}\rangle=0.28(4)$, and $\langle S_{\rm n}\rangle=0.44(4)$.

Key words ^{28}P, β-NMR, nuclear magnetic moment, exotic nuclei

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1 Introduction

Proton-rich unstable nucleus ^{28}P ($I^{\pi}=3^{+}$, $T_{1/2}$= 270.3 ms)[1] has one proton in the $2s_{1/2}$ orbital outside the ^{27}Si core, with relatively small proton separation energy of 2.065 MeV, hence it may have proton halo structure, which may be responsible for the abrupt increase of the reaction cross section of ^{28}P on Si target at intermediate energies reported by Z. H. Liu et al.[2]. The magnetic moment of this nucleus has always been of interest. No successful measurement, however, has been done until now. We tried to measure it years ago using polarization transfer in the low energy nuclear reaction ^{28}Si(p,n)^{28}P and simply found it difficult. One difficulty may be the selection of implantation material. Si was known as a good implantation material for P isotopes, at that time, from the successful measurement of the magnetic moment of ^{29}P. However, in the case of ^{28}P, the Q moment may be very large compared with $Q(=0)$ for ^{29}P ($I^{\pi}=1/2^{+}$), hence the spin relaxation from the quadrupole interactions may be significant. The

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magnetic moment of ^{28}P was estimated to be rather small, which give us very large $eqQ/\mu H$ ratio. In the present work, we have successfully measured the magnetic moment of ^{28}P using Pt as an implantation material, utilizing its small magnetic moment, to study structure of this nucleus. Combined with the magnetic moment of its mirror partner ^{28}Al, we can separate orbital angular momenta and intrinsic spins.

2 Experimental

The present experiment was performed at NIRS (National Institute of Radiological Sciences). The ^{28}P nuclei were produced through the charge exchange reaction bombarding 2 mm thick Be target with a primary beam of ^{28}Si at 100 AMeV, provided by the heavy ion synchrotron HIMAC. The ^{28}P nuclei were separated out with a fragment separator installed in the secondary beam line SB2. By selecting ejection angle $\theta = 0.7°$ and momentum $\Delta p/p_0 = -2.0\%$, nuclear spin polarization was introduced in the ^{28}P nuclei. Thus polarized ^{28}P nuclei were slowed down and were implanted in a Pt foil cooled down to 15 K, placed under a strong magnetic field of 0.9 T ($FM = \pm 15$ kHz) or 1.0 T ($FM = \pm 50$ kHz), to preserve polarization. β-rays emitted from ^{28}P were detected by a pair of plastic-scintillation-counter telescopes placed above and below the Pt catcher relative to the polarization direction. To reduce background β-ray counts a 0.5 mm-thick Cu plate was used as an absorber. The β-NMR was detected by means of the β-ray asymmetry.

3 Results and discussion

Typical momentum distribution and the polarization of the secondary beam ^{28}P are shown in Fig. 1. Center momentum is significantly decelerated from the primary beam velocity, and the relatively large polarization is observed, which may show a strong influence from the pick-up process in the present charge exchange process.

The β-NMR spectra are shown in Fig. 2. From the spectra, g-factor of ^{28}P was determined to be $|g(^{28}\mathrm{P})| = 0.1028(27)$, correcting 0.10% of the theoretical diamagnetism and including 0.27% of Knight shift [3] in the error, from which the magnetic moment was deduced by the well known expression $\mu = gI$.

The obtained magnetic moment $|\mu(^{28}\mathrm{P})| = 0.309(9)\ \mu_{\mathrm{N}}$ is very much quenched from the Schmidt value +0.88, but is well reproduced by the shell model value +0.306 obtained by the OXBASH code[4]. This agreement, at least, confirms the contribution of the valence $2s_{1/2}$ proton in main configuration, as is speculated from the reaction cross-section data.

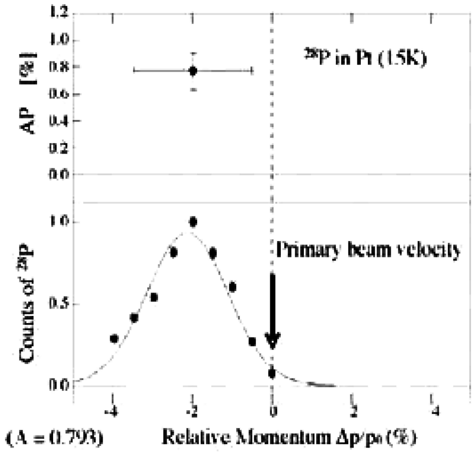

Fig. 1. Polarization as function of momentum.

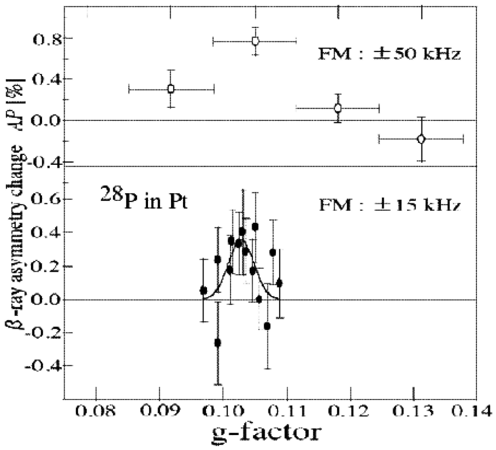

Fig. 2. NMR spectra.

Comparing nuclear moments of mirror pairs, information on the motion of nucleons inside nucleus can be extracted with less ambiguity, because of the mirror symmetry. The total orbital angular momentum $\langle l_z \rangle$ and the intrinsic spin $\langle S_z \rangle$ can be separated from the iso-scalar moment $\mu(i,s)$, as is shown in equation (1)[5, 6], assuming free nucleon values for g-factors. On the other hand, $\langle \tau_3 l_z \rangle$ and $\langle \tau_3 S_z \rangle$ can be derived from the iso-vector moment $\mu(i,v)$ and the Gamow-Teller matrix element $\int \sigma$ as shown in Eq. (2).

$$\begin{aligned}\mu(i,s) &= \frac{1}{2}\{\mu(^{28}\mathrm{P}) + \mu(^{28}\mathrm{Al})\} = \\ &\quad \frac{J}{2} + \left(\mu_{\mathrm{p}} + \mu_{\mathrm{n}} - \frac{1}{2}\right)\langle S_z \rangle, \langle l_z \rangle = J - \langle S_z \rangle,\end{aligned} \tag{1}$$

$$\begin{aligned}\mu(i,\nu) = {} & \frac{1}{2}\{\mu(^{28}\mathrm{P})-\mu(^{28}\mathrm{Al})= \\ & \frac{1}{2}\langle\tau_3 l_z+(\mu_\mathrm{p}-\mu_\mathrm{n})\langle\tau_3 S_z\rangle,\langle\tau_3 S_z\rangle= \\ & \frac{1}{2}\sqrt{\frac{2TJ}{J+1}}\int\sigma\ , \qquad (2)\end{aligned}$$

$\langle l_z\rangle$ and $\langle S_z\rangle$ are deduced to be 2.28(1) and 0.73(1), respectively, from the present magnetic moment of ^{28}P and the known magnetic moment of the mirror partner, $|\mu(^{28}\mathrm{Al})| = 3.242(5)\mu_\mathrm{N}$[7]. The ft-value of the β transition from the ground state of ^{28}P to the IAS (isobaric analogue state) in the excited state of ^{28}Si at 9.314 MeV, is given as $ft = 2925(111)$ s, from the f and t values given from the end-point energy[8] and the branching ratio (0.113(4))[1], respectively. Considering Fermi matrix element $|\int 1|^2=2$, the Gamow-Teller matrix element $\int\sigma$, hence $|\langle\tau_3 S_z\rangle| = 0.16(6)$ is given. Combined with this information, we obtain expectation values as,

$$\langle l_\mathrm{p}\rangle = 0.43(29),\ \langle l_\mathrm{n}\rangle = 1.85(29),$$

$$\langle S_\mathrm{p}\rangle = 0.28(4),\ \langle S_\mathrm{n}\rangle = 0.44(4),$$

while the shell model prediction gives,

$$\langle l_\mathrm{p}\rangle_\mathrm{SM} = 0.62,\ \langle l_\mathrm{n}\rangle_\mathrm{SM} = 1.87,$$

$$\langle S_\mathrm{p}\rangle_\mathrm{SM} = 0.17,\ \langle S_\mathrm{n}\rangle_\mathrm{SM} = 0.34,$$

where $\langle l_\mathrm{p}\rangle$ denotes the z-component of the orbital angular momentum for proton group, etc. Although the magnetic moment is well reproduced by the shell model calculation, the individual angular momenta are not necessarily reproduced well (Fig. 3). The shell model prediction seems to develop configuration mixing too much. Especially, the total spin is too small.

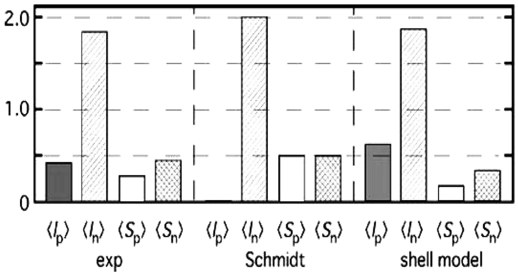

Fig. 3. Decomposition of nuclear spin.

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