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Development of polarized Xe gas target for neutron experiment at J-PARC

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Abstract. At the Materials and Life science experimental Facility (MLF) in J-PARC, an experiment of detecting a neutron polarizing ability caused by a neutron-nuclear spin correlation at a resonant peak of ^{129}Xe is planned. We evaluated measurable quantities based on a neutron optical theorem, developed a polarized Xe gas system, and carried out a feasibility test of our apparatus.

1. Introduction

Recent developments of spin exchange optical pumping (SEOP) technique for polarizing noble gases have enabled to obtain the gases of $10^{-2} - 10^{-1}$ nuclear spin polarization at pressures of $10^{-1} - 10^{0}$ atm [1]. The polarized gases have been applied extensively in various fields. For example, the polarized Xe gas has been utilized as a probe for investigating nuclear electric dipole moment (EDM) by measuring Larmor precession precisely in a fundamental physics [2], a standard sample for nuclear magnetic resonance (NMR) method in a material science, and a blood flow tracer in a medical industry [3]. For low energy neutron experiments, the Xe gas and solid are also expected to be utilized as high polarized targets and samples under a low magnetic field. For example, an NMR-modulated neutron scattering is proposed in order to study slow conformational changes in liquids by measuring a neutron scattering from the polarized Xe nuclei which are solved in water solutions [4]. It is also interesting to measure a correlation term $\boldsymbol{s} \cdot \boldsymbol{I}$ of a neutron spin $\boldsymbol{s}$ and a target nuclear spin $\boldsymbol{I}$ with a high polarized Xe target for a verification of a neutron optical theorem (NOPT). However, there seem to be few experimental data on the $\boldsymbol{s} \cdot \boldsymbol{I}$ term of Xe at the present [5]. At a Materials and Life science experimental Facility (MLF) in J-PARC, an experiment of detecting a neutron polarizing ability caused by the $\boldsymbol{s} \cdot \boldsymbol{I}$ term at a resonant peak of ^{129}Xe is planned, and a polarized Xe gas target based on the SEOP has been developed. This paper reports on the plan and preparative status of our experiment.

2. Evaluation of neutron-nuclear spin correlation based on the NOPT

According to the NOPT, a propagation of low energy neutron through target material is described by a forward scattering amplitude f,

$$f = A + B\hat{\boldsymbol{s}} \cdot \hat{\boldsymbol{I}} + C\hat{\boldsymbol{s}} \cdot \hat{\boldsymbol{k}} + D\hat{\boldsymbol{s}} \cdot (\hat{\boldsymbol{k}} \times \hat{\boldsymbol{I}}), \tag{1}$$

where $\hat{\boldsymbol{s}}$, $\hat{\boldsymbol{I}}$ and $\hat{\boldsymbol{k}}$ denote unit vectors representing directions of a neutron spin, a target nuclear spin and a incident neutron momentum, respectively [6, 7]. The complex coefficients A, B, C, D are described as a function of a neutron energy E_n though they are considered to be constant below a thermal neutron energy. A and B represent parity conserving (PC) amplitudes caused by strong interactions, and C and D represent parity non-conserving (PNC) amplitudes caused by weak interactions. In Eq. (1), imaginary parts of the $\boldsymbol{s} \cdot \boldsymbol{I}$, $\boldsymbol{s} \cdot \boldsymbol{k}$ and $\boldsymbol{s} \cdot (\boldsymbol{k} \times \boldsymbol{I})$ terms induce neutron spin $\boldsymbol{s}$ dependent cross sections $\Delta\sigma_I$, $\Delta\sigma_k$ and $\Delta\sigma_{k\times I}$ relative to directions of $\boldsymbol{I}$, $\boldsymbol{k}$ and $\boldsymbol{k} \times \boldsymbol{I}$, while their real parts induce neutron spin rotations ϕ_I, ϕ_k and $\phi_{k\times I}$ around axes of $\boldsymbol{I}$, $\boldsymbol{k}$ and $\boldsymbol{k} \times \boldsymbol{I}$.

Observations of the PNC amplitudes are important for study of neutron fundamental physics. The PNC effects caused by the $\boldsymbol{s} \cdot \boldsymbol{k}$ term have been estimated about 10^{-7}, and verified by observing helicity asymmetries A_k of the spin dependent cross sections $\Delta\sigma_k$ with proton-proton scatterings [8]. However, they have been found to be enhanced in neutron-nucleus scatterings, especially, values of A_k at p-wave resonances of ^{139}La, ^{131}Xe and so on, have reached up to $10^{-2} - 10^{-1}$ [9, 10, 11]. These enhancements are explained by a model based on a interference between the p-wave and its neighboring s-wave resonances [12]. According to the model, A_k and ϕ_k are described as a function of E_n with a parity mixing matrix element xW and Briet-Wigner (B-W) resonance formula. In particular, both A_k and ϕ_k of ^{139}La have been observed with cold and epithermal neutrons, and they were consistent with predictions deduced from the model [11, 13, 14, 15]. The result suggests that the NOPT on the $\boldsymbol{s} \cdot \boldsymbol{k}$ term is valid up to an epithermal neutron energy region. But for verification of the NOPT based on Eq. (1), it becomes necessary to measure the quantities caused by the $\boldsymbol{s} \cdot \boldsymbol{I}$ and $\boldsymbol{s} \cdot (\boldsymbol{k} \times \boldsymbol{I})$ terms with polarized targets.

The enhancement of the PNC effect at the p-wave resonance is considered to be useful for detecting a time reversal non-conserving (TRNC) effect caused by the $\boldsymbol{s} \cdot (\boldsymbol{k} \times \boldsymbol{I})$ term [7, 16]. For realizing to measure the TRNC effect, it becomes a key technique to reduce an affect of neutron spin rotation frequency ω_I and ω_H caused by the $\boldsymbol{s} \cdot \boldsymbol{I}$ term and an external magnetic field $\boldsymbol{H}$ for holding target polarizations, where $\omega_I (= d\phi_I/dt)$ and ω_H are known as a pseudo-magnetic frequency and a Larmor precession frequency. Especially it is important to comprehend ω_I as a function of E_n because ω_I was predicted to increase in vicinities of resonant peaks [17, 18].

We attempted to evaluate measurable quantities of ^{129}Xe$(I = 1/2)$ and ^{131}Xe$(I = 3/2)$ caused by the $\boldsymbol{s} \cdot \boldsymbol{I}$ term. As the PNC effects are normally much smaller than the PC effects, Eq. (1) is approximately described as $f \approx A + B\hat{\boldsymbol{s}} \cdot \hat{\boldsymbol{I}}$, and $\Delta\sigma_I$ and ω_I are given as

$$\Delta\sigma_I = \frac{4\pi}{k} Im(f_+ - f_-) \qquad \omega_I = -\frac{2\pi N_I \hbar}{m_n} Re(f_+ - f_-), \tag{2}$$

where N_I and m_n denote a number density of target and a neutron mass, and $f_+(f_-)$ is the amplitude f with the neutron spin $\boldsymbol{s}$ parallel (anti-parallel) to the target spin $\boldsymbol{I}$ [18]. It is considered to be difficult to estimate neutron scattering amplitudes caused by the $\boldsymbol{s} \cdot \boldsymbol{I}$ term because a complete set of resonance parameters is not known in most case, at least not for bound-state resonances ($E_n < 0$) [19]. But the amplitudes caused by the $\boldsymbol{s} \cdot \boldsymbol{I}$ term at resonant peaks with strong spin selectivity could be estimated by using Eq. (2) and the B-W formula [17, 18]. Fig. 1 represents the estimated $\Delta\sigma_I$ and ω_I of ^{129}Xe as a function of E_n around a 9.6 eV s-wave resonant peak (total angular momentum $J = 1$). This resonance selects neutrons

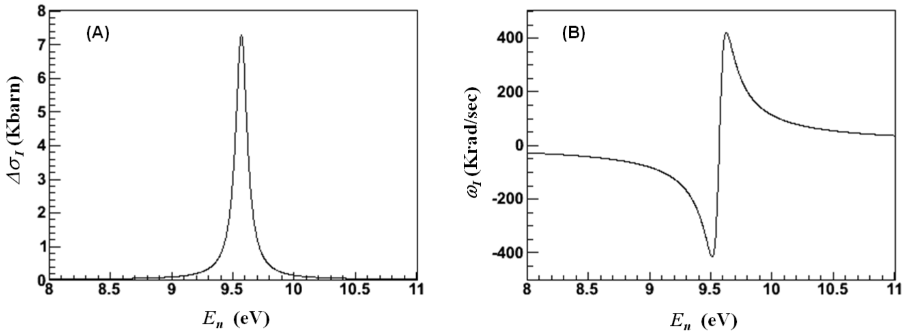

Figure 1. Estimated values of (A) spin dependent cross section $\Delta\sigma_I$ and (B) spin rotation frequency ω_I at 9.6 eV s-wave resonant peak of ^{129}Xe

with spin $s = +1/2$ based on a conservation of an angular momentum. Fig. 1 was calculated by using resonance parameters of ^{129}Xe based on the evaluated data in ENDF/B-VII.0 [20] and by assuming a ^{129}Xe gas of 1 atm pressure. It predicts that $\Delta\sigma_I$ and ω_I depend on E_n strongly and increase at the resonant peak. Especially ω_I exhibits a dispersion curve as a function of E_n, and its maximum value is 4×10^5 rad/sec which corresponds to a pseudo-magnetic field $\boldsymbol{H}^* \approx 2.2$ mTesla. We also calculated ω_I of ^{131}Xe at a 14.4 eV s-wave resonant peak ($J = 2$), and obtained the maximum value of $\omega_I \approx 1 \times 10^7$ rad/sec which corresponds to $\boldsymbol{H}^* \approx 57$ mTesla.

3. Plan to measure neutron-nuclear spin correlation at BL10 in J-PARC

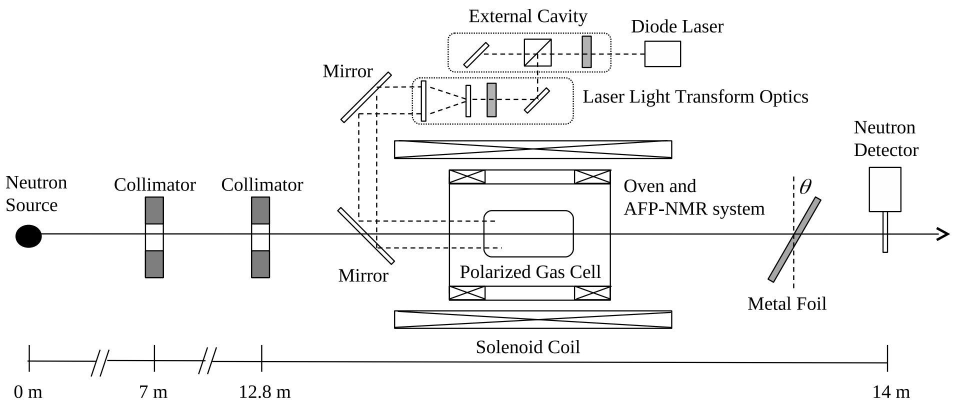

Figure 2. Experimental apparatus for detecting neutron polarizing ability of ^{129}Xe

As the first step to detect the $\boldsymbol{s} \cdot \boldsymbol{I}$ term, we will measure a neutron polarizing ability at the 9.6 eV s-wave resonant peak of ^{129}Xe when unpolarized neutrons transmit through a polarized Xe target. It has an advantage of realizing the measurement without a neutron spin polarizer though its predicted value is smaller than that of a spin dependent cross section asymmetry $A_I = (\sigma_{I+} - \sigma_{I-})/(\sigma_{I+} + \sigma_{I-})$, where σ_{I+} and σ_{I-} denote the cross section with $\boldsymbol{s}$ parallel and anti-parallel to $\boldsymbol{I}$.

Our experimental apparatus is schematically shown in Fig. 2. Our experiment will be carried out at a neutron beam line 10 (BL10) of the MLF in J-PARC [21]. Pulsed neutron beams supplied from a spallation neutron source transmit through collimators, a polarized Xe gas target, a referential metal foil, and are counted by a neutron detector placed at 14 m position apart from the source. The movable collimators placed at 7 m and 12.8 m positions are used for adjusting the neutron beam size and intensity. The metal foil mounted on a goniometer is used in order to compensate time fluctuations of the detector by comparing resonant peak amplitudes between the foil and ^{129}Xe measured with the same detector. A ratio R_x between neutron transmissions with the target polarized and unpolarized is expressed as

$$R_x = \cosh(N_x \sigma_x l_x \rho P_x), \tag{3}$$

where N_x, σ_x, l_x, P_x denote a number density, cross section, thickness and polarization of target nuclei x, respectively. Spin dependent parameters ρ of the target become 1/3 of ^{129}Xe and 1 of ^{3}He. Its neutron polarization is given as $P_n = \sqrt{1 - R_x^{-2}}$ with R_x in Eq. (3).

The Xe gas target is polarized by utilizing an in-situ SEOP system developed for a polarized ^{3}He neutron spin filter at J-PARC [22, 23]. It is designed compactly for mounting on experimental tables in narrow areas of beam lines. It consists of a diode laser (nLight VSA-100-796 DL) driven at an output power of ∼47 W, an external cavity for narrowing wave length of laser, laser light transform optics, and a solenoid coil of 20 cm in diameter and 30 cm long for holding the target polarization. A Xe gas of ∼1 atm is contained in a cylindrical glass cell about 3 cm in diameter and $5 - 10$ cm long with a N_2 gas and a small amount of Rb. Atomic spins of Rb are polarized by a resonance absorption of a circularly polarized laser light of a 795 nm wave length, and Xe nuclear spins are polarized by the spin exchange with the polarized Rb atoms. The cell is mounted in an oven of 10 cm in diameter and 12 cm long. The oven is made of aluminum (Al) and placed at a center of the solenoid coil. A temperature inside the oven is kept to $350 - 450$ Kelvin for obtaining a Rb vapor. Around the cell, a pickup coil and a drive coil are mounted for the NMR measurement by an adiabatic fast passage (AFP) method. The AFP-NMR system is very useful for evaluating and monitoring a polarization P_{Xe} of the Xe cell by periodic measurements of NMR signals during beam experiments. These components of the SEOP system are set in a box of $40 \times 40 \times 60$ cm^3 size for shielding laser light.

We guess that practical values of $\Delta R_{Xe} = 1 - R_{Xe}$ in Eq. (3) will be $10^{-3} - 10^{-2}$. Actually ΔR_{Xe} is estimated about 0.003 with a natural Xe gas of 15 atm·cm thickness and 0.012 with an enriched ^{129}Xe gas of 10 atm·cm thickness if a realizable $P_{Xe} \sim 0.2$ is assumed. For obtaining the Xe gas cell with a practical thickness l_{Xe} and P_{Xe}, it is important to know the pressure dependence of P_{Xe} and the effect of the relaxation due to collisions between Xe atom and the cell wall, which is expressed by the wall relaxation time t_w [24]. Time evolution of a noble gas x polarization $P_x(t)$ is described as

$$P_x(t) = P_{Rb} \frac{\gamma_{se}}{\gamma_{se} + \Gamma_w} (1 - e^{-(\gamma_{se} + \Gamma_w)t}) = \bar{P}_x (1 - e^{-\gamma_{gr} t}), \tag{4}$$

where P_{Rb}, γ_{se}, Γ_w and γ_{gr} denote Rb atom polarization, Rb-x spin exchange rate, wall relaxation rate and growth rate of P_x. $\bar{P}_x$ represents an attainable value of $P_x(t)$, and a inverse of Γ_w corresponds to t_w. In the case of Xe, it is known that P_{Xe} decreases with increasing a Xe atom pressure because of a decrement of P_{Rb} by a increment of a Rb spin destruction rate due to the effect of Rb−Xe binary collisions. While, for reducing the wall relaxation, some papers have reported to obtain long values of t_w more than 20 minutes by coating inner surfaces of borosilicate glass cells (Pyrex) with SurfaSil [24, 25]. For neutron experiments, however, it is required to select cell materials with their neutron cross sections as small as possible. We attempted to measure t_w of the cell filled with a natural Xe gas of 2.6 atm pressure in a spherical quartz glass of 3 cm diameter, and obtained long t_w more than 50 minutes. This result suggests that quartz glass becomes a suitable material for the polarized Xe cell.

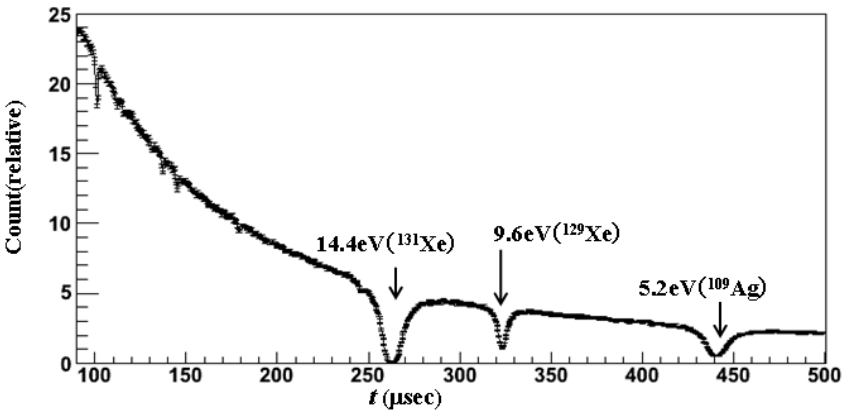

Figure 3. Time of flight (TOF) spectrum of neutrons transmitting through unpolarized Xe cell

4. Feasibility test for measuring neutron polarizing ability of ^{129}Xe

According to the apparatus in Fig. 2, we have attempted to check the compensation method of time fluctuations by comparing resonant peak amplitudes between the Xe cell and the referential metal foil. In the test, a cylindrical quartz cell of 5 cm long filled with a natural Xe gas of 3 atm pressure, a silver (Ag) foil of 10 μm thickness mounted on a goniometer, and a Li glass scintillator of 1 mm thickness, were used as the cell, metal foil and neutron detector. Fig. 3 represents a time of flight (TOF) spectrum of neutrons transmitting through the unpolarized Xe cell. It suggests that the Xe cell and Ag foil are suitable thickness because the both resonant peaks at 9.6 eV of ^{129}Xe and 5.2 eV of ^{109}Ag could be distinguished with enough peak amplitudes. In Fig. 2, an effective thickness l_{Ag} of the Ag foil depends on a inclination angle θ of the foil relative to the neutron beam direction, and changes by rotating the goniometer. We attempted to demonstrate a sensitivity of our system by detecting a slight change of the ratio $\Delta R(\theta) = 1 - r_{res}(\theta)/r_{res}(0^\circ)$ as a function of θ, where $r_{res}(\theta)$ represents the amplitude ratio between the 9.6 eV resonant peak of ^{129}Xe and the 5.2 eV resonant peak of ^{109}Ag. In the beam test during a few hours, $\Delta R(30^\circ) = 0.060 \pm 0.014$ and $\Delta R(20^\circ) = 0.013 \pm 0.011$ have been obtained. This preliminary result suggests that the sensitivity corresponding to $\Delta R_{Xe} = 1 - R_{Xe}$ in Eq. (3) reaches to $\sim 10^{-2}$ in statistical errors.

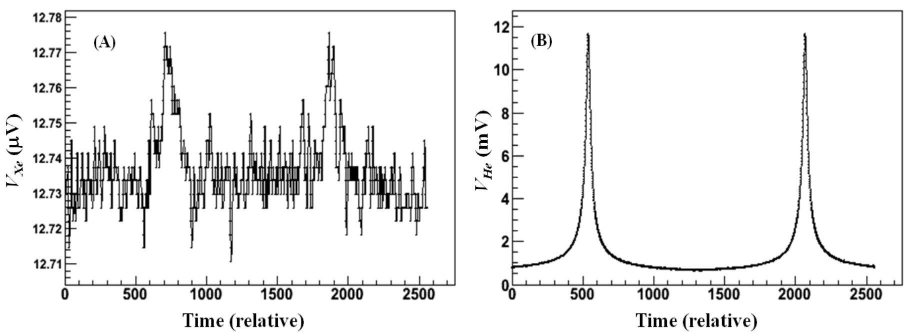

Figure 4. Typical NMR amplitudes (A) V_{Xe} of ^{129}Xe and (B) V_{He} of ^{3}He observed at ν_{res} =50 kHz

For monitoring the polarization of the cell during beam experiments, an AFP-NMR system has been developed [26, 27]. It can work inside of the Al oven in our SEOP system, and detect NMR signals both of ^{3}He and ^{129}Xe at a same resonant frequency ν_{res}. For demonstrating an ability of our NMR system, the measurement of P_{He} of a polarized ^{3}He filter with cold neutrons has been carried out with observing NMR signal amplitudes V_{He} of ^{3}He periodically. According to Eq. (3), P_{He} was determined from the ratio R_{He} between neutron transmissions with the ^{3}He filter polarized and unpolarized. In the test, a cylindrical glass cell of 5 cm long containing in a ^{3}He gas of 3.2 atm was used as the ^{3}He filter. Fig. 4 represents the typical NMR amplitudes V_{Xe} of ^{129}Xe and V_{He} of ^{3}He observed at ν_{res} =50 kHz. Fig. 5 represents time evolution process of P_{He} deduced from R_{He} and V_{He} from a start time ($t = 0$) of the optical pumping. By fitting the observed values with Eq. (4), $\bar{P}_{He} = 0.26 \pm 0.02$ was obtained from Fig. 5 (A). It corresponds to $V_{He} \approx 18.3$ mV deduced from Fig. 5 (B). While, $\gamma_{gr}^{-1} = 9.54 \pm 0.19$ hours was also obtained as a growth time of Fig. 5 (B). It was consistent with the γ_{gr}^{-1} of Fig. 5 (A) in statistical errors. We guess that the observed P_{He} might be small due to the lack of adjustment of the laser light transform optics because $P_{He} \geq 0.6$ is obtained by using our SEOP system usually. By using the correlation between P_{He} and V_{He} obtained from this test, the polarization P_{Xe} of the Xe cell can be deduced from the NMR amplitude V_{Xe}. Actually we could obtain about 0.01 as P_{Xe} corresponding to the amplitude V_{Xe} in Fig. 4 (A).

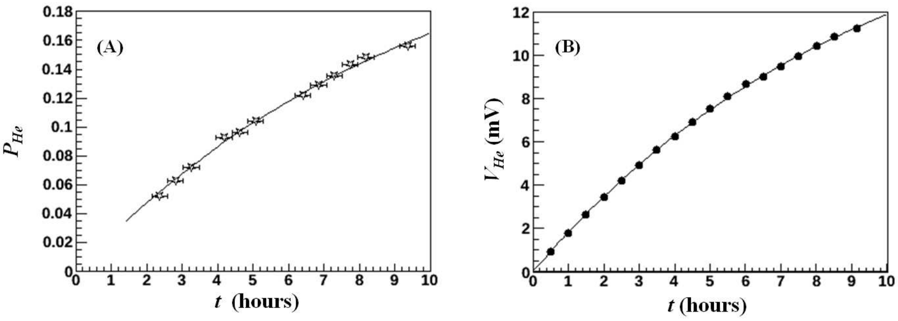

Figure 5. Time evolutions of (A) P_{He} deduced from R_{He} and (B) V_{He} of NMR as a function of time t from start time ($t = 0$) of the optical pumping

5. Summary

We mentioned interest in the measurement of the $\boldsymbol{s} \cdot \boldsymbol{I}$ term as a function of E_n for verification of the NOPT, and reported the experimental plan and feasibility tests for detecting the neutron polarizing ability at the 9.6 eV resonant peak of ^{129}Xe. Although the statistical accuracy of ΔR_{Xe} is dominated by the counting capability of our system at the present, it will be achieved to $\sim 10^{-3}$ by improving the detector and data acquisition system. For obtaining the practical l_{Xe} and P_{Xe}, we will attempt to optimize conditions of the SEOP system, and prepare a Xe cell filled with an enriched ^{129}Xe gas of a low pressure in order to avoid a decrement of P_{Xe} with increasing a Xe pressure. For the study on the $\boldsymbol{s} \cdot \boldsymbol{I}$ term in detail, however, the measurements of A_I and ω_I with polarized neutron beams are indispensable. Actually, by using $P_n = 0.5$ polarized neutron beams, $A_I \approx 0.038$ is expected with a natural Xe cell of $P_{Xe} = 0.2$ and 15 atm·cm thickness though $\Delta R_{Xe} \approx 0.003$ is estimated with the same cell. For realizing these measurements, developments of a polarized proton filter and a high pressure ^{3}He filter will be desirable as neutron spin filters at the MLF in J-PARC [28].

Acknowledgments
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