Axion-like-Particles Search with the nEDM Spectrometer at PSI

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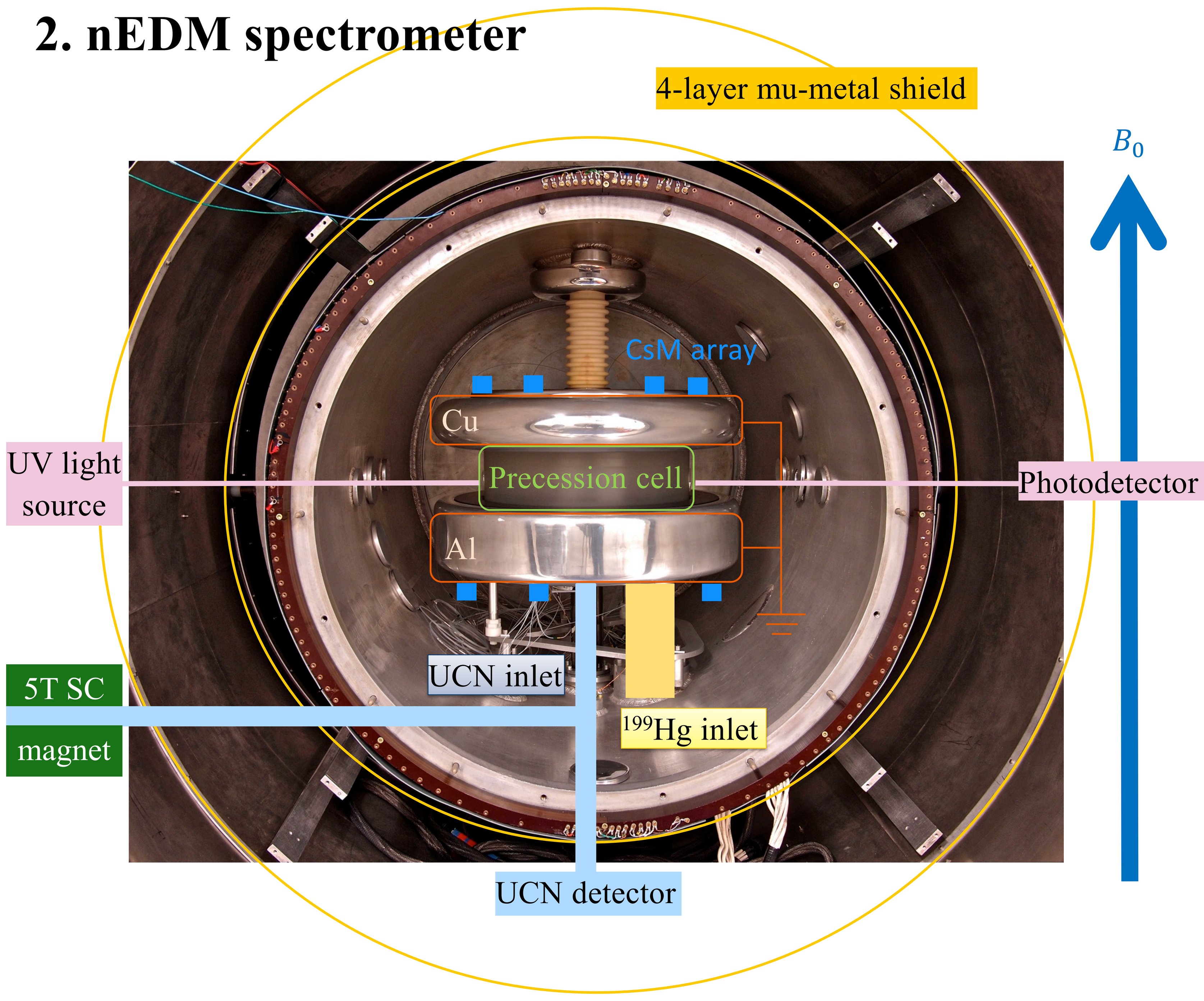
1. Motivation

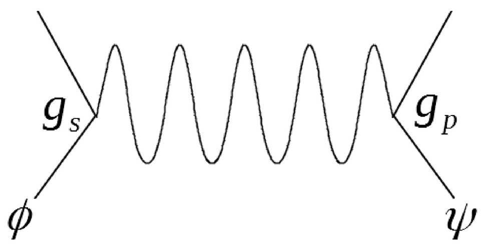
The non-observation of CP violation in the strong interaction is one of the motivations for physicists to search for signals of physics beyond the standard model (BSM). The introduction of a “fifth force” on the macroscopic level attracts great attentions in the fields of particle physics, cosmology and astroparticle physics. A short-range spin-dependent interaction, which could be mediated by axions[1] and axion-like particles (ALPs), involving the product of g_s and g_p couplings, was brought forward in 1984[2].

Using the nEDM spectrometer at PSI, we search for an interaction between polarized ultracold neutrons (UCN) and unpolarized nucleons in the bulk material of the chamber wall, which could be mediated by ALPs[3]. The spin-dependent interaction could be considered as a pseudo-magnetic field changing the spin-precession frequencies of stored UCN and ^{199}Hg atoms. With careful investigation on the frequency ratio of the two species, a limit on the product of couplings $g_s g_p$ can be derived. With an upgrade of the apparatus, data were taken in 2017. Followed by a dedicated analysis in progress, a sensitivity gain by an order of magnitude compared to the preceding experiment[3] is expected. This study targets to achieve a new limit on the product of $g_s g_p$ with an improved sensitivity, constraining the allowed parameter space of BSM theories.

2. nEDM spectrometer



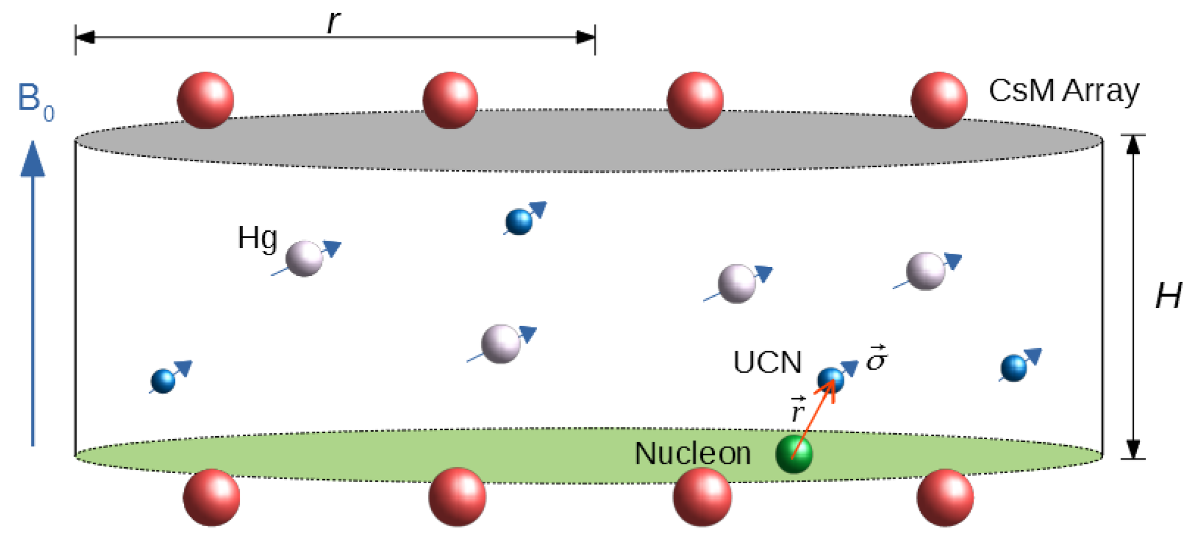
3. Short-range spin-dependent interaction



g_s / g_p: scalar / pseudoscalar coupling constant
ϕ : unpolarized particle
ψ : polarized particle

Spin-dependent potential: $V(\boldsymbol{r}) = g_s g_p \frac{(\hbar c)^2}{8\pi m c^2}(\hat{\boldsymbol{\sigma}}\cdot\hat{\boldsymbol{r}})\left(\frac{1}{r\lambda}+\frac{1}{r^2}\right)\mathrm{e}^{-r/\lambda}$

Pseudo-magnetic field: $b(z) = g_s g_p \frac{\hbar\lambda N}{2\gamma m}\left(1-\mathrm{e}^{-d/\lambda}\right)\left(\mathrm{e}^{-z/\lambda}\right)$ N: nucleon density



$B_0 = 1\ \mu\mathrm{T}$
$H = 12$ cm
$r = 23.5$ cm

$$b_{\mathrm{UCN}} = \int_{-H/2}^{H/2} g_s g_p \frac{\hbar\lambda}{2\gamma m}\left(1-\mathrm{e}^{-d/\lambda}\right)\left[N_{\mathrm{bottom}}\mathrm{e}^{-\frac{z+H/2}{\lambda}} - N_{\mathrm{top}}\mathrm{e}^{-\frac{-z+H/2}{\lambda}}\right]\rho_{\mathrm{UCN}}(z)\,\mathrm{d}z$$

$$\rho_{\mathrm{UCN}}(z) = \frac{1}{H}\left(1+\frac{12\langle z\rangle}{H^2}z\right)$$

$\langle z\rangle$: center-of-mass offset, (-2)~(-4) mm

4. Crossing-point analysis

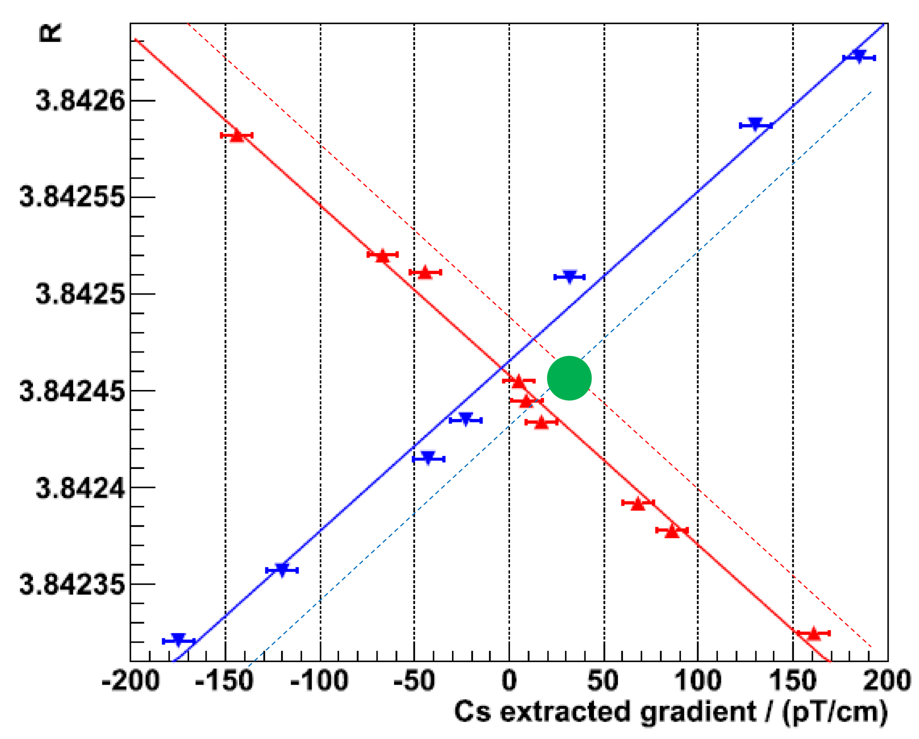
- Frequency ratio of UCN and ^{199}Hg co-magnetometer

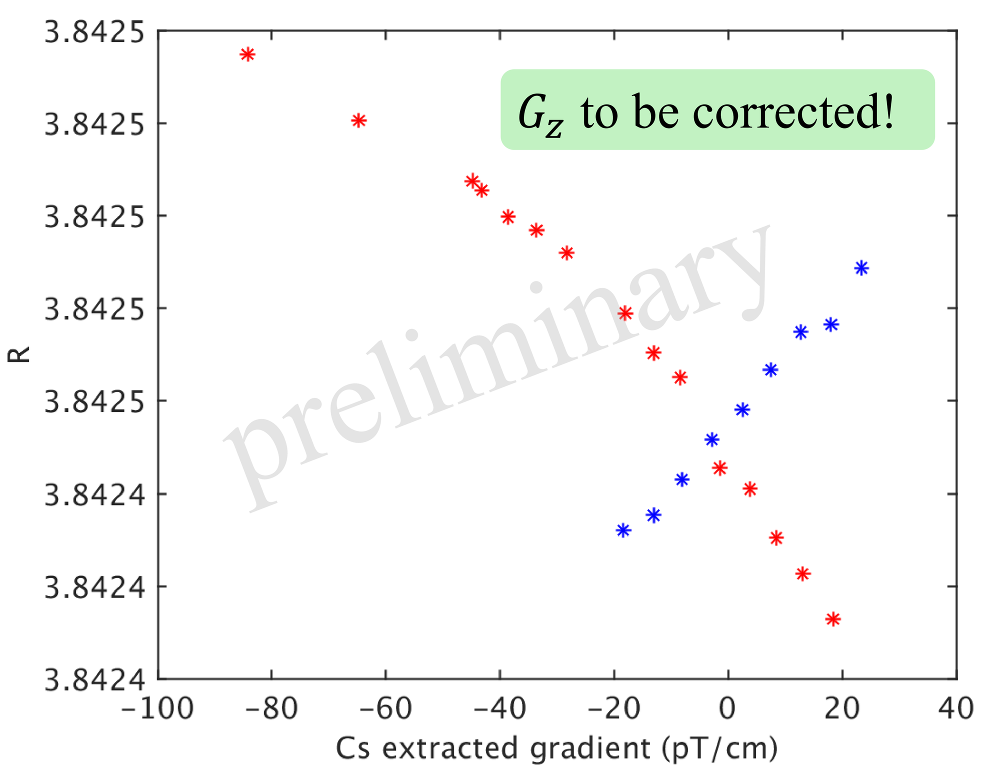
$$R^{\uparrow\downarrow} = \frac{f_n}{f_{\mathrm{Hg}}} = \frac{\gamma_n}{\gamma_{\mathrm{Hg}}}\left(1+\delta_{\mathrm{Grav}}+\delta_{\mathrm{Trans}}\pm\boxed{\frac{b_{\mathrm{UCN}}}{B_0}}\right)$$

δ_{Grav}: gravitational shift ($\delta_{\mathrm{Grav}} = \pm\frac{\langle z\rangle}{B_0}G_z = \pm\frac{\langle z\rangle}{B_0}\frac{\mathrm{d}B_z}{\mathrm{d}z}$, $\langle z\rangle < 0$)

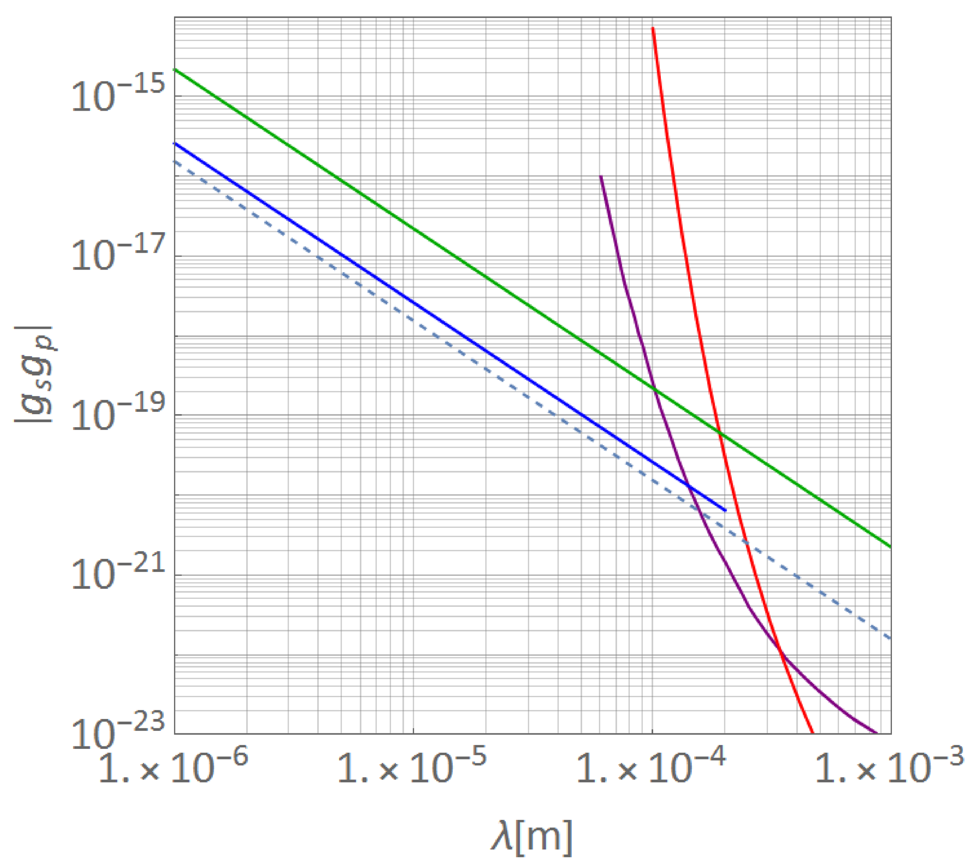
δ_{Trans}: transverse shift ($\delta_{\mathrm{Trans}} = \frac{\langle B_T{}^2\rangle}{2B_0{}^2}$)

- Observe R value under different gradients G_z





5. Estimated sensitivity gain in $g_s g_p$



- Reduced error:

$\delta_{\mathrm{Grav}} = \pm\frac{\langle z\rangle}{B_0}G_z$: G_z error 8 pT/cm → 1 pT/cm

$\delta_{\mathrm{Trans}} = \frac{\langle B_T{}^2\rangle}{2B_0{}^2}$: $\langle B_T{}^2\rangle$ error 0.5 nT^2 / 0.7 nT^2 → 0.3 nT^2

References:
[1] R. D. Peccei and H. R. Quinn, PRL 38(25):1440-1443 (1977).
[2] J. E. Moody and F. Wilczek, PRD 30(1):130-138 (1984).
[3] S. Afach et al., PLB 745: 58-63 (2015).

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