Constraint on CP-odd short range interaction from neutron diffraction experiment

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UCN Workshop, SPb, Russia, 8-14 June 2009

Introduction

Short range Yukawa-type potential of fermion-fermion interaction

$$V_{SP}(\mathbf{r}) = \frac{\hbar^2 g_S g_P}{8\pi m}(\mathbf{n}\cdot\sigma)\left(\frac{1}{r\lambda}+\frac{1}{r^2}\right)e^{-r/\lambda} \qquad \mathbf{n} = \frac{\mathbf{r}}{|\mathbf{r}|}$$

J.E.Moody and Frank Wilczek, Phys.Rev.D **30** (1984) 130.

For the case of neutron diffraction this potential should give an additional spin dependence amplitude of scattering

$$f_{sp}(\mathbf{g}) = -\frac{m}{2\pi\hbar^2}V_{sp}(\mathbf{g}) = -\frac{m}{2\pi\hbar^2}\int\limits_{V=1} e^{i\mathbf{gr}}V_{sp}(\mathbf{r})d^3r = -\frac{2m}{\hbar^2}\int\limits_{V=1} V(r)\frac{\sin gr}{g}rdr$$

$$g = \frac{2\pi}{d}$$ - reciprocal lattice vector

Neutron diffraction

Direct calculation for neutron-nucleon interaction gives

$$V_{sp}(g) = -\frac{i\hbar^2 g_s g_p}{2m}\frac{g\lambda^2}{1+g^2\lambda^2}(\boldsymbol{\sigma}\mathbf{n}_\mathbf{g})$$

$$\mathbf{n}_\mathbf{g} = \mathbf{g}/|\mathbf{g}|$$

g-harmonics of neutron interaction with the crystal will be

$$V_g^{SP} = -iF_g^{SP} e^{i\Phi_g^{SP}} \frac{\hbar^2 g_s g_p}{2mV_c}\frac{g\lambda^2}{1+g^2\lambda^2}(\boldsymbol{\sigma}\mathbf{n}_g)$$

$$f_g^{SP} \equiv F_g^{SP} e^{i\Phi_g^{SP}} = \sum_i A_i \cdot e^{i\mathbf{g}\mathbf{r}_i}$$ is a structure factor

A_i is the mass of i-nucleus

Neutron wave function close to the Bragg condition

$$\psi(\mathbf{r}) = e^{ikr} + \frac{V_g^N}{E_k - E_{k_g}} e^{ik_g r} \equiv e^{ikr}\left[1 - \frac{U_g^N}{2\Delta_g} e^{igr}\right],$$

$E_k = \hbar^2 k^2/2m$ and $E_{k_g} = \hbar^2 k_g^2/2m$ are the neutron energies in |k> and |k+g> states

$V_g^N = \hbar^2 U_g^N/2m$ is a g-harmonics of nuclear potential

$\Delta_g = (k_g^2 - k^2)/2$ is a deviation from Bragg condition

Pseudomagnetic field

$$\tilde{V}_{SP} = <\psi(\mathbf{r})|V_{SP}(\mathbf{r})|\psi(\mathbf{r})> = \frac{U_g^N}{\Delta_g}|\tilde{V}_g^{SP}|\sin\Phi_g^{SP} =$$

$$= \frac{U_g^N}{\Delta_g} F_g^{SP} \frac{\hbar^2 g_s g_p}{2mV_c} \frac{g\lambda^2}{1+g^2\lambda^2}(\sigma\mathbf{n}_g)\sin\Phi_g^{SP} \equiv V_{SP}(\sigma\mathbf{n}_g).$$

deviation from Bragg condition

phase shift

Time of neutron passage through the crystal

Angle of neutron spin rotation

$$\varphi_{SP} = \frac{2V_{SP}}{\hbar}\tau$$

For crystal with a center of symmetry $\varphi_{SP} \equiv 0$ because $\Phi_g^{SP} \equiv 0$

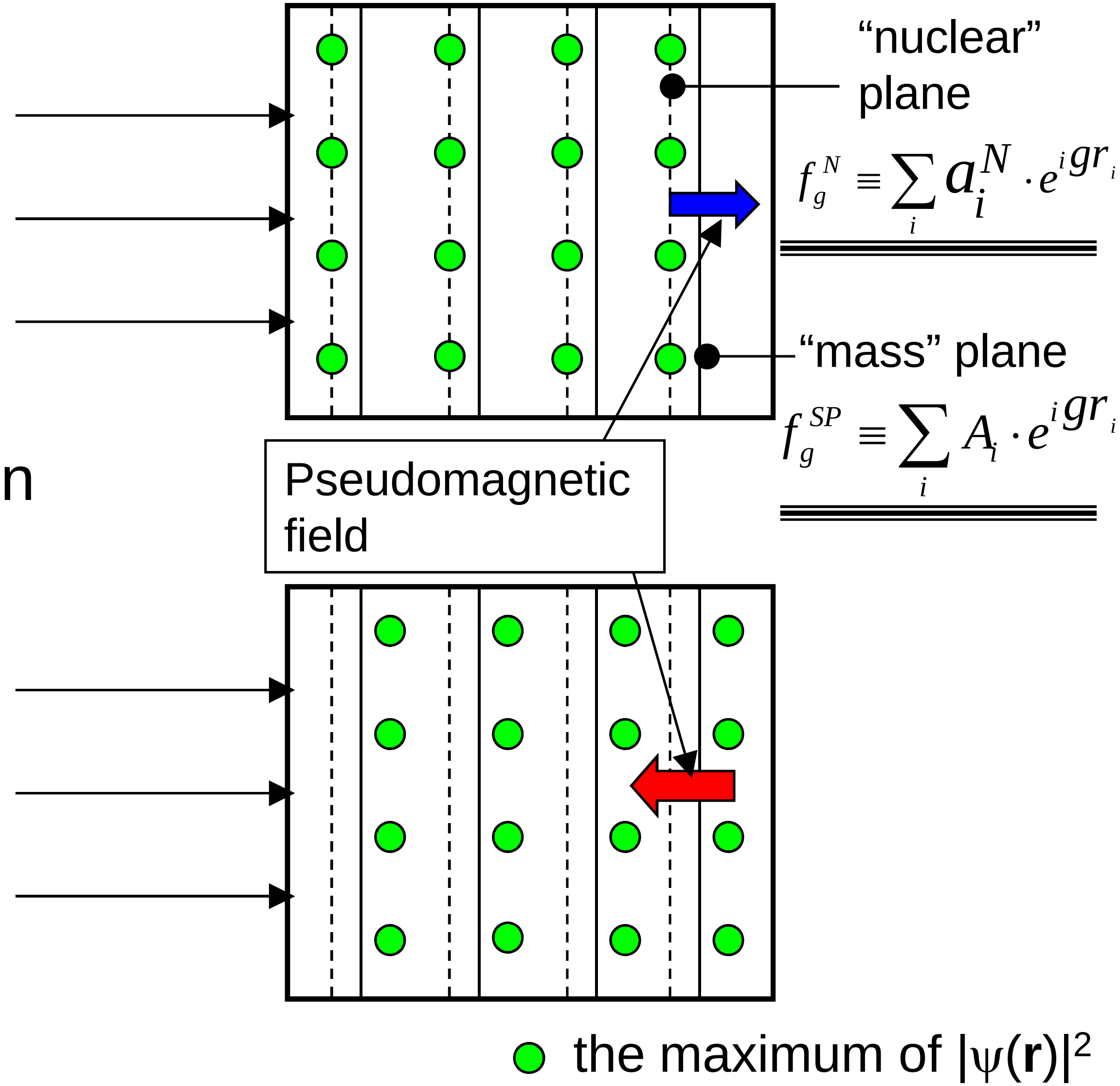
Neutron passage through the crystal

$E_n > E_g$

Neutron energy
of exact Bragg condition

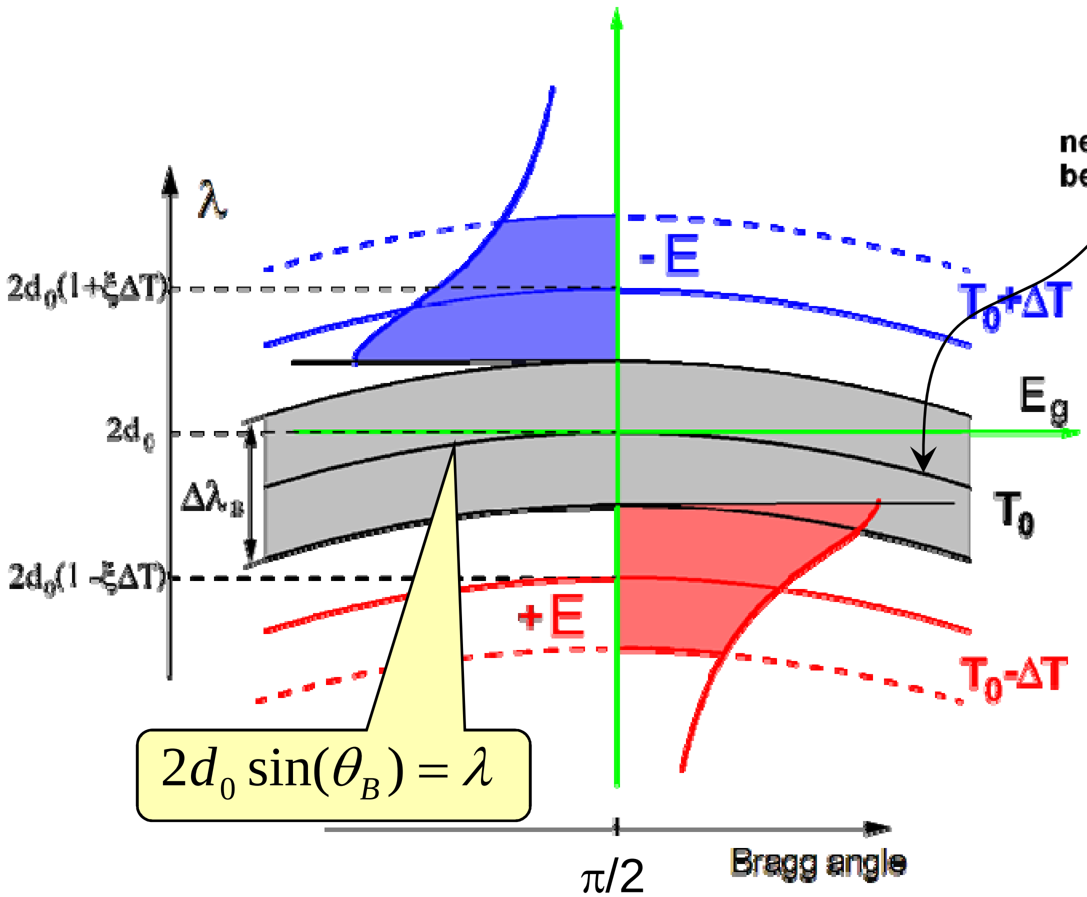
$$E_g = \hbar^2 g^2 / 8m$$

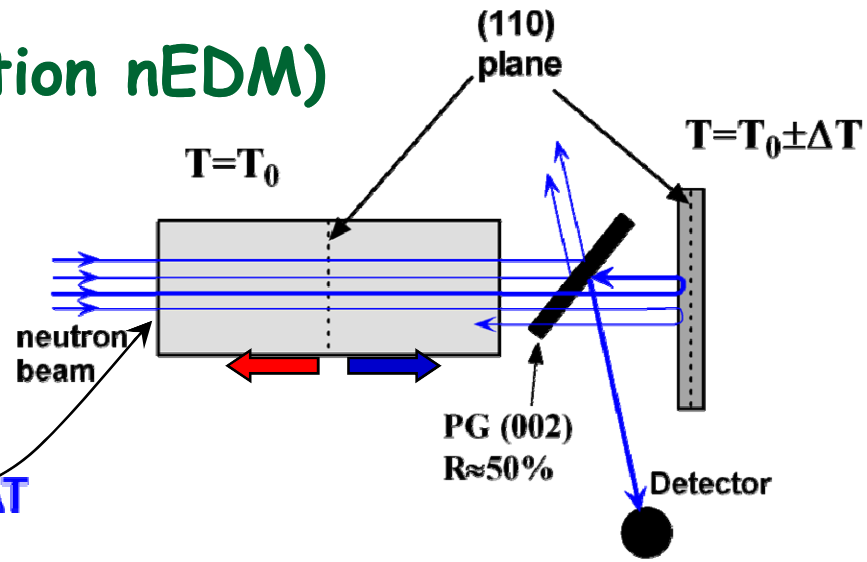
$E_n < E_g$



Scheme of the experiment

(the same as crystal-diffraction nEDM)





For (110) plane of quartz crystal

$\Delta T = 1^0 K$

$\Delta\lambda/\lambda \approx 10^{-5} = \Delta\lambda_B/\lambda$

Sensitivity

For (110) plane of quartz crystal and $\Delta_B = \frac{U_g^N}{\Delta_g} = 0.5$, $g = 2.56 \cdot 10^8\,\mathrm{cm}^{-1}$, $F_g^{SP} = 51$, $\sin(\Phi_g^{SP}) = 0.41$, $V_c = 113\,\mathrm{Å}^3$. The angle of spin rotation due to considered potential will be

$$\varphi_{SP} = 0.36 \cdot 10^{24}[cm^{-3}] \cdot \frac{g_S g_P}{g^2 + 1/\lambda^2} L$$

where L is the crystal length.

$\sigma(\varphi_{SP}) \sim 2 \cdot 10^{-6}$ can be reached for 100 day of the statistic accumulation. That allows to give such a constraint

$$g_S g_P < 10^{-31}[cm^2] \cdot (g^2 + 1/\lambda^2)$$

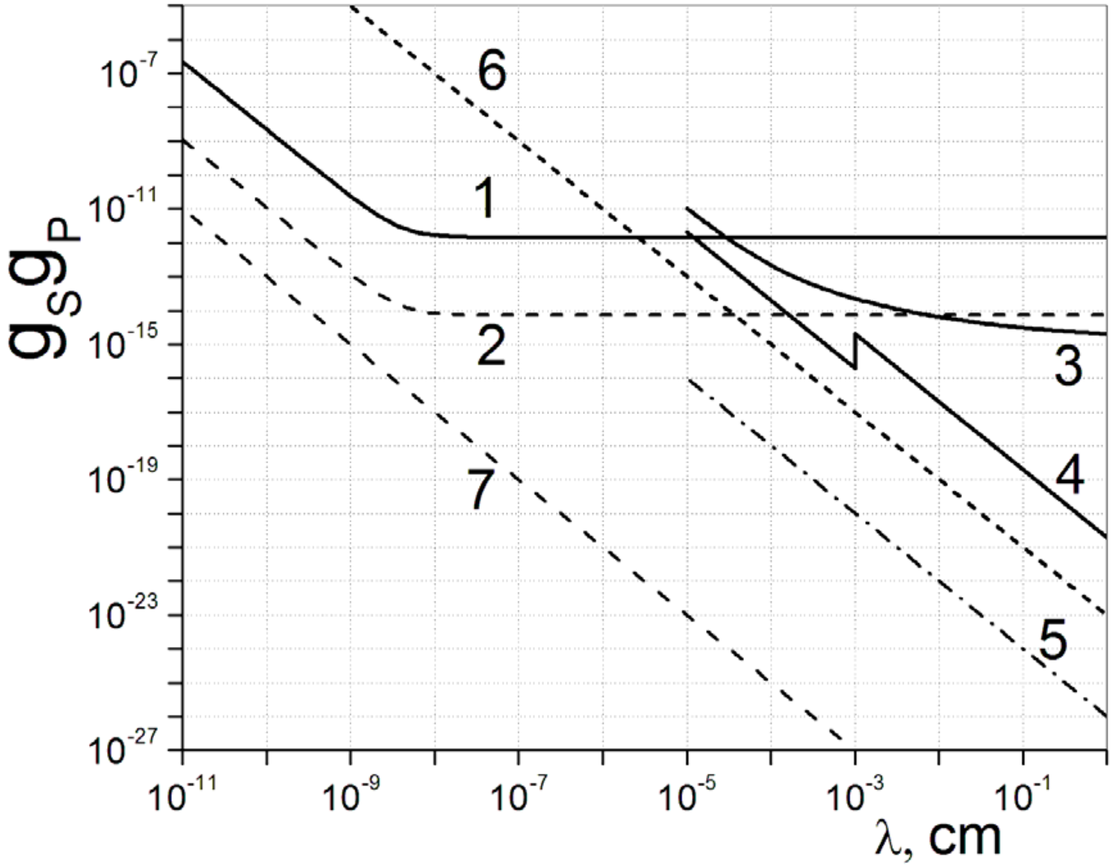
for the L=50 cm.

Current experimental result from crystal-diffraction nEDM experiment *)

$$g_S g_P < 4 \cdot 10^{-29}[cm^2] \cdot (g^2 + 1/\lambda^2)$$

*) V.V. Fedorov, M. Jentchel, I.A. Kuznetsov, E.G. Lapin, E. Lelievre-berna, V. Nesvizhevsky, A. Petoukhov, S.Yu. Semenikhin, T. Soldner, V.V. Voronin, Nuclear Physics A, DOI: 10.1016/j.nuclphysa.2009.05.117

Constraints on the ($g_s g_p$;λ)



(1) this work
(2) is possible improvement of this method,
(3) is gravitational level experiment [1]
(4) is the UCN depolarization [2]
(5) is proposal [3],
(6) and (7) are the predictions of axion model with $\theta \sim 1$ and $\theta \sim 10^{-10}$ correspondingly [2]

[1] S.Baessler, V.V.Nesvizhevsky, K.V.Protasov, A.Yu.Voronin, Phys.Rev.D **75** (2007) 075006.
[2] A.P. Serebrov, ArXiv:0902.1056v1 [nucl-ex] 6 Feb 2009.
[3] O. Zimmer, ArXiv:0810.3215v1 [nucl-ex] 17 Oct 2008.

Conclusion

- Crystal diffraction experiment can give the best constrain on pseudomagnetic field for the $\lambda < 10^{-5}$ cm
- This effect can give a systematic for nEDM experiment
- These two effects will be different for different crystallographic planes, so in the case of nonzero effect they can be separated using different planes for measurement.