Hunting for Majoranality
of
Neutrinos in Muon Decay

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Ref.: T. F, S. Kanda(Riken), D. Nomura(KEK), and K. Shimomura(KEK),**arXiv:1908.01630**, submitted to Phys. Rev. D

- We propose a new experiment to search for a T-violating process in muon decay and the Majoranality of the neutrinos.
- Tiny neutrino mass is explained by seesaw mechanism, which leads to Majorana neutrino.
- In the presence of $V+A$ interactions, muon decay ratio depends on whether the neutrinos are Dirac or Majorana.
- This signal of Majoranality appears as the T-violating term without the contamination of the SM background.
- So the non-null signal of T-violating term indicates the Majoranality of the neutrinos.

Contents

2. T-violating term in μ decay.

We consider the effective Hamiltonian,

$$H_W = \frac{G_F}{\sqrt{2}} \left[j^{\dagger}_{L\alpha} j^{\alpha}_{L} + \lambda j^{\dagger}_{R\alpha} j^{\alpha}_{R} + \kappa \left(j^{\dagger}_{L\alpha} j^{\alpha}_{R} + j^{\dagger}_{R\alpha} j^{\alpha}_{L} \right) \right],$$

where

$$\begin{aligned} j_{L\alpha} &\equiv \textstyle\sum_{l=e,\mu,\tau} \bar{l}(x)\gamma_\alpha(1-\gamma_5)\nu_{lL}(x), \\ j_{R\alpha} &\equiv \textstyle\sum_{l=e,\mu,\tau} \bar{l}(x)\gamma_\alpha(1+\gamma_5)\nu'_{lR}(x). \end{aligned}$$

weak eigenstates are related with mass eigen states via

$$\nu_{lL} = \sum_j U_{lj} N_{jL}, \quad \nu'_{lR} = \sum_j V_{lj} N_{jR}$$

$$M \sim \sum_{\substack{\gamma = \mathrm{S,V,T} \\ \epsilon,\mu = \mathrm{L,R} \\ (n,m)}} g^{\gamma}_{\epsilon\mu} \langle \bar{\mathrm{e}}_{\epsilon} | \Gamma^{\gamma} | (\nu_{\mathrm{e}})_n \rangle \langle (\bar{\nu}_{\mu})_m | \Gamma_{\gamma} | \mu_{\mu} \rangle$$

$$\nu_{lL} = \sum_{j=1}^{3} \left(U_{lj}\nu_{jL} + S_{lj}(N_{jR})^c \right)$$

$$\nu_{lR} = \sum_{j=1}^{3} \left(T^*_{lj}(\nu_{jL})^c + V^*_{lj}N_{jR} \right)$$

with $l = e,\ \mu,\ \tau$.

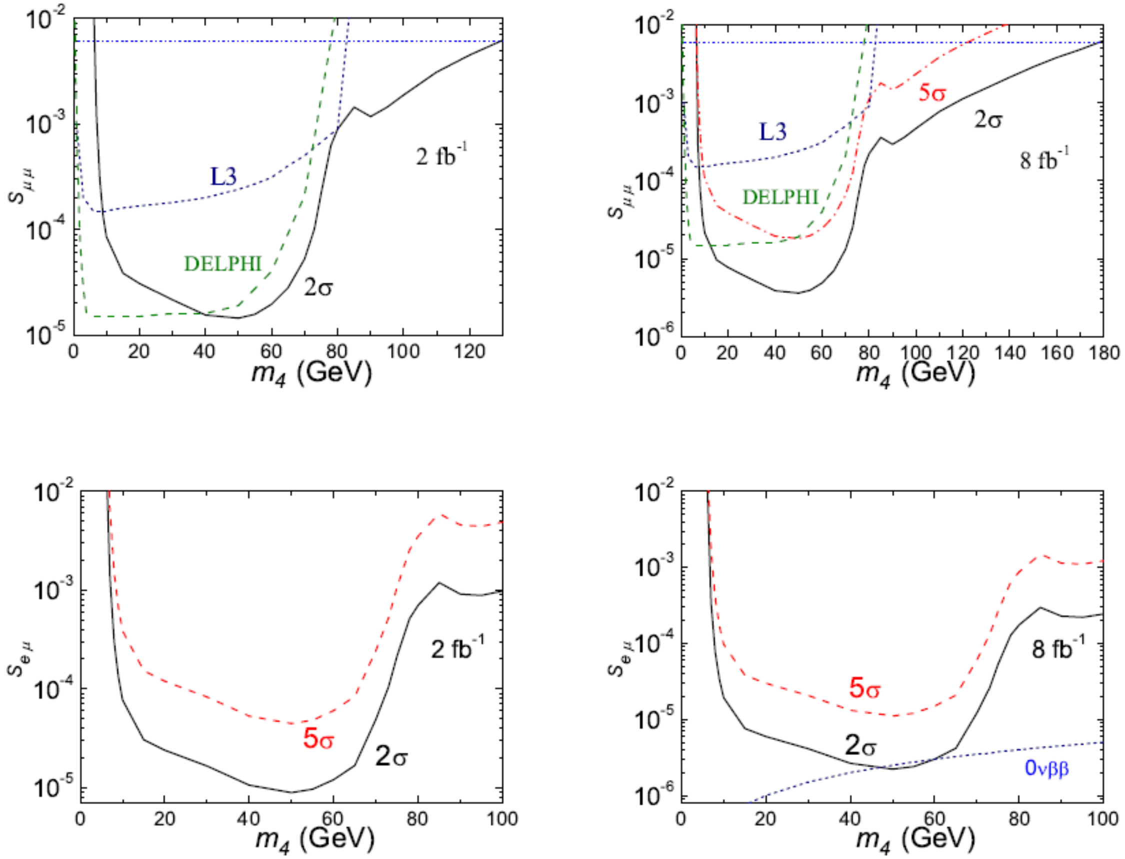
the constraint of λ from the $0\nu\beta\beta$, $\eta_\lambda = \lambda|\sum_{j=1}^{3} U_{ej}T^*_{ej}|$:

TABLE II. Upper bounds on the effective Majorana neutrino mass $m_{\beta\beta}$ and parameter η_λ associated with right-handed currents mechanism imposed by current constraints on the $0\nu\beta\beta$-decay half-life for nuclei of experimental interest. The calculation is performed with NMEs obtained within the QRPA with partial restoration of the isospin symmetry (see Table I). The upper limits on $m_{\beta\beta}$ and η_λ are deduced for a coexistence of the $m_{\beta\beta}$ and λ mechanisms (Maximum) and for the case $\eta_\lambda = 0$ or $\eta_\nu = 0$ (On axis). $g_A = 1.269$ and CP conservation ($\psi = 0$) are assumed.

	^{48}Ca	^{76}Ge	^{82}Se	^{100}Mo	^{116}Cd	^{130}Te	^{136}Xe
$T_{1/2}^{0\nu-exp}$ [yrs]	2.0 10^{22}	5.3 10^{25}	2.5 10^{23}	1.1 10^{24}	1.7 10^{23}	4.0 10^{24}	1.07 10^{26}
Ref.	[25]	[26]	[27]	[28]	[29]	[30]	[31]
$m_{\beta\beta}$ [eV]	23.8	0.185	1.45	0.484	1.55	0.379	0.128
η_λ	2.24 10^{-5}	3.11 10^{-7}	1.65 10^{-6}	5.25 10^{-7}	1.84 10^{-6}	4.87 10^{-7}	1.70 10^{-7}
				for $\eta_\lambda = 0$			
$m_{\beta\beta}$ [eV]	23.7	0.182	1.43	0.477	1.53	0.374	0.126
				for $m_{\beta\beta} = 0$			
η_λ	2.23 10^{-5}	3.07 10^{-7}	1.63 10^{-6}	5.18 10^{-7}	1.81 10^{-6}	4.80 10^{-7}	1.67 10^{-7}

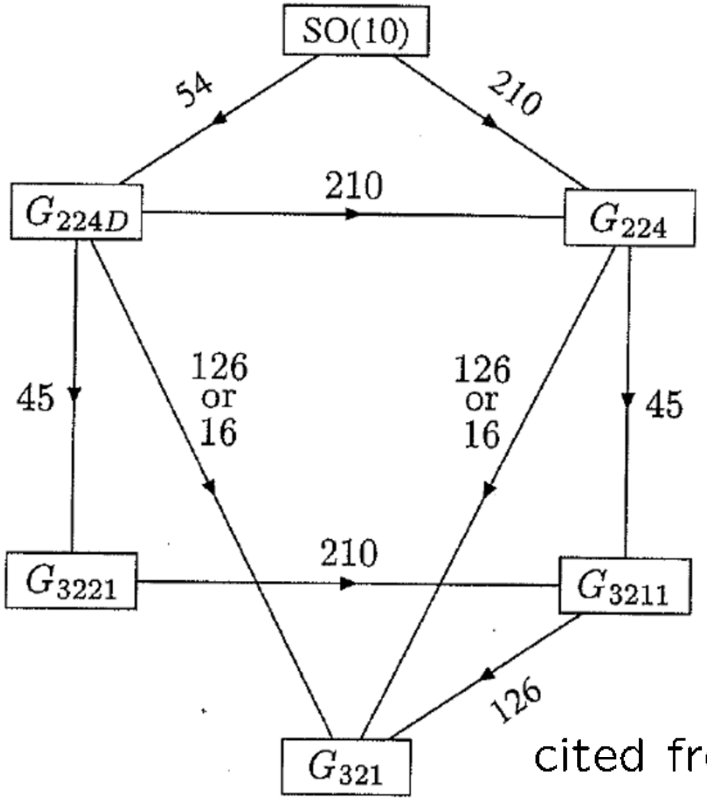
Simkovic et al., 1804.04223

S_{lj}, T_{lj} values are theoretically free and only bounded by obserbations:



Tao-Han et al. JHEP (2009)

Some interesting chains of symmetry breaing from SO(10) to the SM which includes L-R symmetric group.



cited from Mohapatra's text book.

D is $L \leftrightarrow R$ synmetry. $g_L = g_R,\ U = V^*$

We have the other breaking

$$G_{SO(10)} = SU(5)\times U(1),\ \{16\} \supset \{10\}_1 + \{\bar{5}\}_{-3} + \{1\}_5$$

Why right-handed current and Majorana neutrino ?

Tiny neutrino mass requires heavy right-handed Majorana neitrino (in any seesaw mechanism).

Fundamental rep. of SO(10) is 16-dim. which includes all SM fermions (and no exotic one) and is the smallest anomaly free group.

$$m_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

$$m_\nu = -m_D^T M_R^{-1} m_D$$

Yukawa coupling $Y_{ij} 16_i 16_j \phi$ and $16 \otimes 16 = 10 + 120 + 126$.

We need two Higgs for nontrivial mixing CKM (MNS) matrix. We need $10 + \overline{126}$.
$126 = (6,1,1) + (\overline{10},3,1) + (10,1,3) + (5,2,2)$
under $SU(4)_c \otimes SU(2)_L \otimes SU(2)_R$

So vev of $(10,1,3)$ induces heavy Right-handed Majorana neutrino, which is crucial for tiny active neutrino mass.

Mass relation

- All the mass matrices are descried by only two fundamental matrices.

$$M_u = c_{10} M_{10} + c_{126} M_{126}$$
$$M_d = M_{10} + M_{126}$$
$$M_D = c_{10} M_{10} - 3 c_{126} M_{126}$$
$$M_e = M_{10} - 3 M_{126}$$
$$M_R = c_R M_{126}$$
$$\rightarrow M_e = c_d \, (M_d + \kappa M_u) \quad (\text{‘GUT relation'})$$

- 13 inputs : 6 quark masses, 3 angles + 1 phase in CKM matrix,
  3 charged-lepton masses.

  ⇒ $|c_d|$ ¿κ d

  ⇒ **predictions in the parameters in the neutrino sector!**

ν'_R makes masses of the neutrinos via seesaw mechanism (Majorana neutrino), which has an additional motivation of baryon number violation via leptogenesis ($n_B/n_\gamma \approx 1 \times 10^{-10}$)

$$Br(\nu'_R \to l_L + H_u^*) \neq Br(\nu'_R \to \overline{l_L} + H_u)$$

and $\Delta L = 2$ transforms to $\Delta B = 2$ via the sphalelon effect $\Delta(B-L) = 0$. This is the robust constituent of GUT like

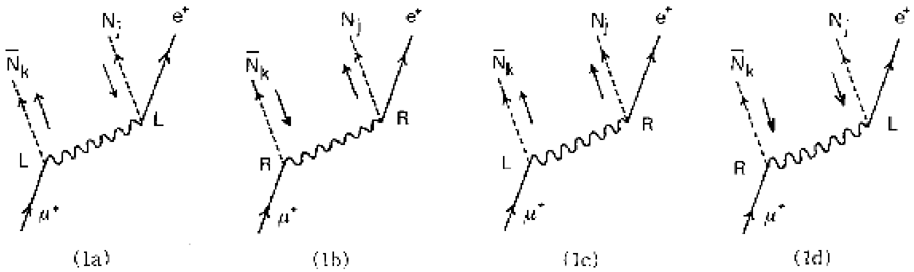
$$SO(10) \to SU(4)_C \otimes SU(2)_L \otimes SU(2)_R \to \text{SM}$$

Left-Right symmetric model: $g_L = g_R$, $U_{ij} = V_{ij}$ at SB scale.

$$\mathcal{L}_N = -h_{ij} l_{L,i} \phi N_j - \frac{1}{2} \sum_i \overline{N_i^C} M_i N_i + h.c.$$

muon decay

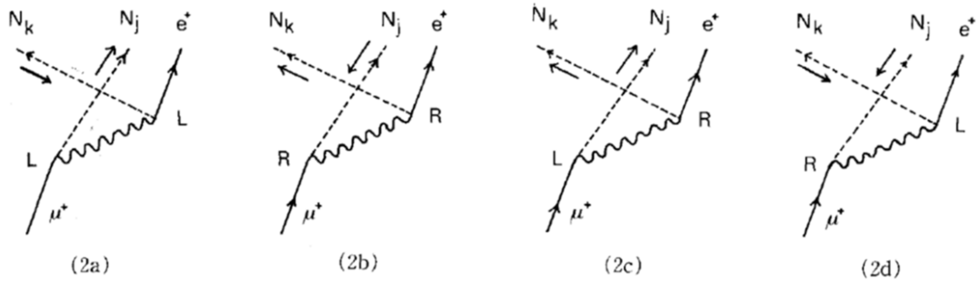
cited from Doi et al., PTP, **67**, 281 (192)



See also

R.E. Shrock, P.L.B112

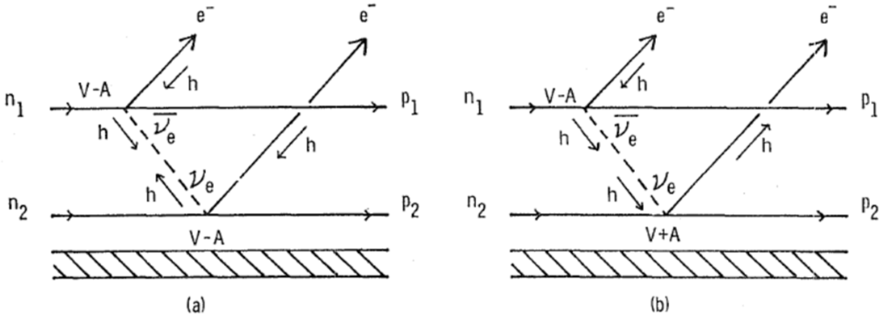
If ν is Majorana, we have additionally



For comparison

Doi et al. PTP Supplement **83** (1985)

$(\beta\beta)_{0\nu}$



$$\Gamma^D = \sum_{j,k} |M_{jk}^{(1)}|^2 \quad \text{for Dirac neutrino}$$

$$\Gamma^M = \sum_{j \geq k} \epsilon_{jk}^2 |M_{jk}^{(1)} + M_{jk}^{(2)}|^2$$

$$= \sum_{j,k} |M_{jk}^{(1)}|^2 + \sum_{j,k} M_{jk}^{(1)*} M_{jk}^{(2)}$$

for Majorana neutrino

$$\frac{d\Gamma^M}{d\mathbf{q}_e} = \frac{m_\mu G_F^2}{3(2\pi)^4}\left\{N(e) \pm \frac{(\mathbf{q}_e\cdot\zeta_\mu)}{E}P(e) \mp \frac{(\mathbf{q}_e\cdot\zeta_e)}{E}Q(e) - \frac{(\mathbf{q}_e\times\zeta_\mu)\cdot(\mathbf{q}_e\times\zeta_e)}{|\mathbf{q}_e|^2}R(e) - \frac{(\mathbf{q}_e\cdot\zeta_\mu)(\mathbf{q}_e\cdot\zeta_e)}{|\mathbf{q}_e|^2}S(e) + \frac{\zeta_\mu\cdot(\mathbf{q}_e\times\zeta_e)}{E}T(e)\right\},$$

$$T(e) = -\epsilon_M \lambda h^I (m_\mu - m_e^2/m_\mu) - 3\kappa\left(v^I m_e - (v^I - 4\kappa z^I)m_\mu\right)$$

$$\approx -\epsilon_M \lambda h^I (m_\mu - m_e^2/m_\mu), \text{ because } v^I \propto m_j/m_\mu,\ \ z^I \propto m_j m_k/m_\mu^2$$

$$h^I \equiv \epsilon_M \sum_{j,k} F_{jk}^{1/2} G_{jk} \mathrm{Im} C'_{jk} \approx \epsilon_M \sum_{j,k} \mathrm{Im} C'_{jk},$$

$$F_{jk} = [1-(m_j+m_k)^2/\Delta^2][1-(m_j-m_k)^2/\Delta^2],$$

$$G_{jk} = 1 + (m_j^2+m_k^2)/\Delta^2 - 2(m_j^2-m_k^2)^2/\Delta^4,$$

$$C'_{jk} = U_{ej}^* V_{ek} V_{\mu j}^* U_{\mu k}$$

$$\Delta^2 \equiv 2m_\mu(W-E). \quad W = \frac{m_\mu^2+m_e^2}{2m_\mu}.$$

Doi et al.

$$\mathcal{H} = \sum_i \{ C_i (\overline{e(x)} \Gamma_i \mu(x))(\overline{\nu_\mu(x)} \Gamma^i \nu_e(x)) + C_i' (\overline{e(x)} \Gamma_i \mu(x))(\overline{\nu_\mu(x)} \Gamma^i \gamma_5 \nu_e(x)) + \text{h.c.} \}$$

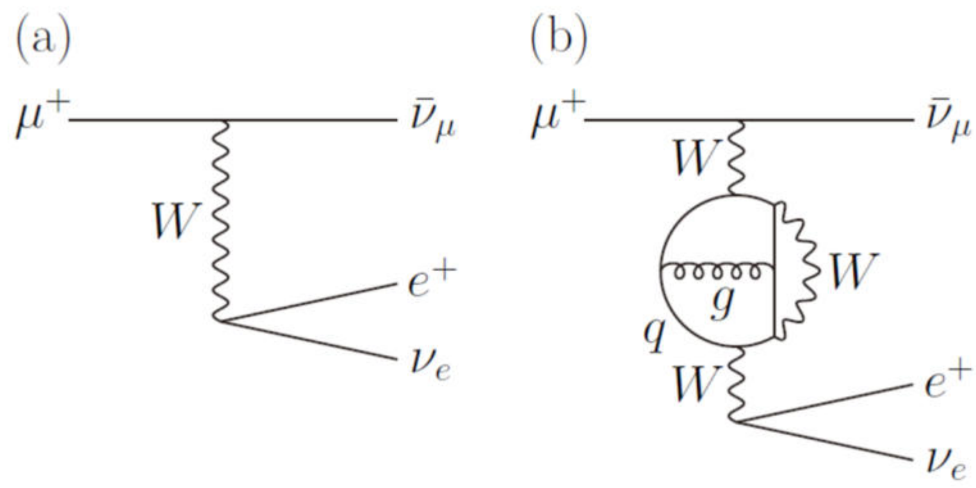
$$\Gamma_S = \mathbf{1}, \qquad \Gamma_V = \gamma^\mu, \qquad \Gamma_A = \gamma^\mu \gamma_5, \qquad \Gamma_P = i\gamma_5, \qquad \Gamma_T = \frac{1}{\sqrt{2}} \sigma^{\mu\nu}.$$

Michel parameters: $a = |C_S|^2 + |C_S'|^2 + |C_P|^2 + |C_P'|^2$ etc.

$$\begin{aligned}
\frac{d^2\Gamma^{(0)}(x, \theta, \phi, \psi)}{dx\, d(\cos\theta)} = \frac{m W^4 A}{32\pi^3} \sqrt{x^2 - x_0^2} \Big\{ & [x(1-x) + \tfrac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0 (1-x)] \\
& - \tfrac{1}{3}\xi \sqrt{x^2 - x_0^2} \cos\theta \left[1 - x + \tfrac{2}{3}\delta\left(4x - 3 - \frac{\mu}{m} x_0 \right) \right] + \\
- \xi' \sqrt{x^2 - x_0^2} \cos\phi \left[1 - x + \tfrac{2}{3}\delta'\left(4x - 3 - \frac{\mu}{m} x_0 \right) \right] & \\
+ \tfrac{1}{3}\xi'' \cos\theta \cos\phi [x(1-x) + \tfrac{2}{3}\rho'(4x^2 - 3x - x_0^2) + \eta' x_0 (1-x)] & \\
+ \sin\theta \sin\phi \cos\psi \left[(1-x) x_0 \frac{3a - 2b - 2c}{3A} + x(1-x) \frac{\alpha}{A} + (x - x_0^2) \frac{2\beta}{3A} \right] & \\
+ \sin\theta \sin\phi \sin\psi \sqrt{x^2 - x_0^2} \left[(1-x) \frac{\alpha'}{A} + \tfrac{2}{3}\left(1 - \frac{\mu}{m} x_0 \right) \frac{\beta'}{A} \right] \Big\}. &
\end{aligned}$$

for Dirac neutrino

3. T-violation in the SM



T-violation decay width is suppressed by the factor δ.

$$\delta = \frac{G_{\mathsf{F}} m_t^2}{8\pi^2\sqrt{2}} \frac{\alpha_s}{4\pi} \frac{1}{16\pi^2} \frac{g^2}{8} J_{CP} \approx 1 \times 10^{-13}.$$

4. Experiment

Positron polarization is determined in the reactions of the annihilation in flight (AIF) $e^+e^- \to 2\gamma$ or of the Bhabha e^+e^- scattering. .

Statistical precision of polarimeter is evaluated by the Figure of Merit (FOM)

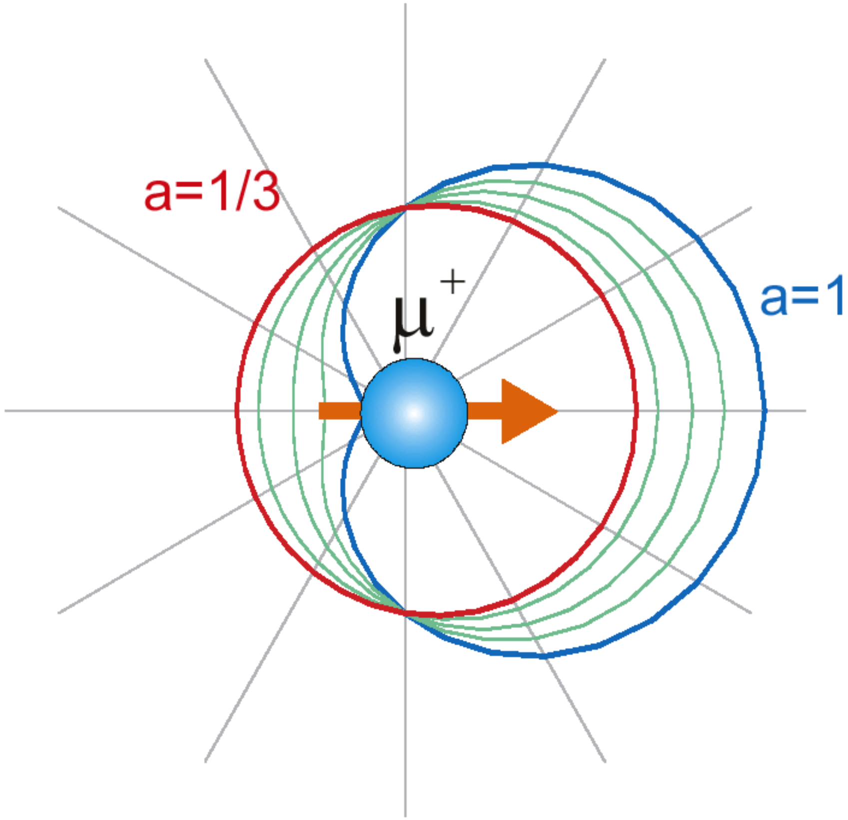
$$F = N\mathcal{A}^2,$$

where

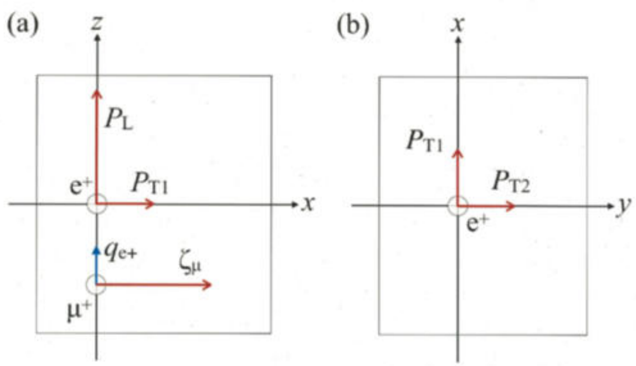
$$\mathcal{A} = \frac{N_+ - N_-}{N_+ + N_-} \equiv \frac{N_+ - N_-}{N}$$

where N_+ and N_- are the number of positrons polarized in parallel and anti-parallel to the axis of interest, respectively.

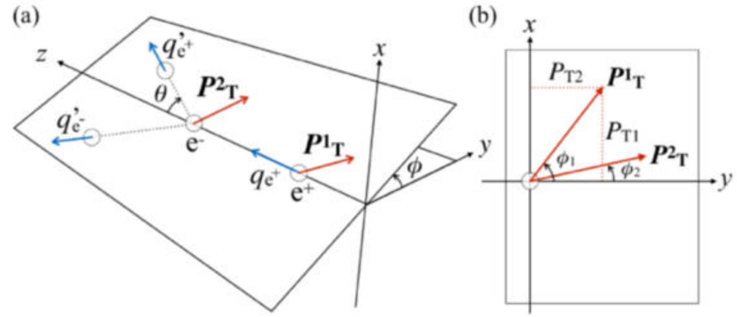
μ^+ Decay Asymmetry



Detail will be described by Adachi



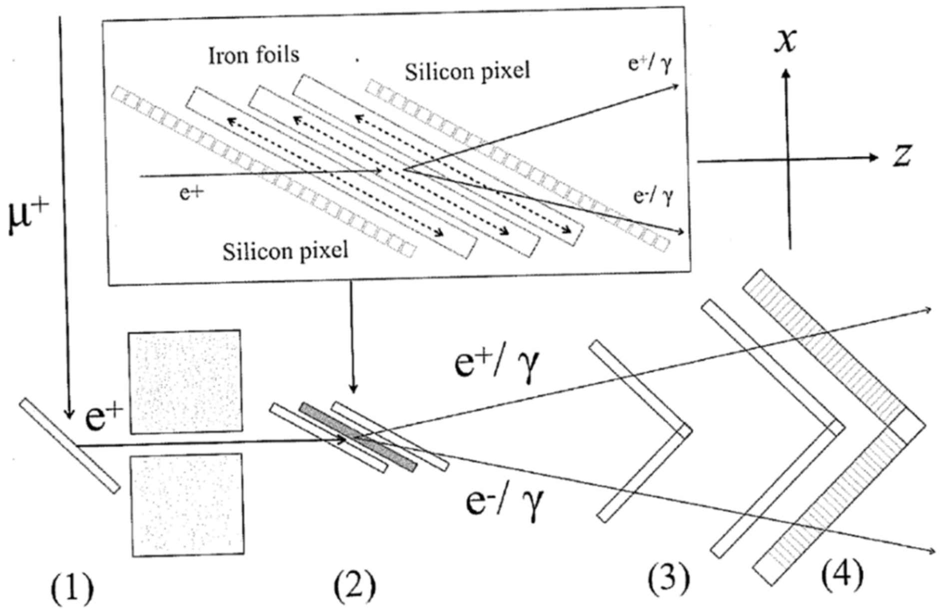
Definition of the positron $\zeta_e = (\mathbf{P}_t, P_L)$.



Schematic of Bhabha scattering

J-PARC MLF MUSE H-Line
25Hz, 100 ns width,
bunch interval of 600ns
$1 \times 10^8\ \mu^+/s$

1) Beryllium stopping plate
2) the spin-analyzingtarget between the silicon pixel detectors
3) the silicon strip detectors for electron/positron tracking
4) the segmented BGO calorimeter for gamma rays



Experimental schematic of the decay positron polarimeter

4.1 Bhabha scattering

(Relativistic $e^- - e^+$ scattering)

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathsf{BHA}} = \frac{\alpha^2(3+\cos^2\theta^*)^2}{4s(1-\cos\theta^*)^2}\,(\,1 - P_{\mathsf{L}}^1 P_{\mathsf{L}}^2 A_{\mathsf{L}}(\theta^*) - |\boldsymbol{P}_{\mathsf{T}}^1||\boldsymbol{P}_{\mathsf{T}}^2| A_{\mathsf{T}}(\theta^*)\cos(2\phi - \phi_1 - \phi_2)\,)\,,$$

in CM system

where the upper indices 1 and 2 in $\mathbf{P}_T$ indicate beam (e^+) and target (e^-), respectively, and

$$A_{\mathsf{L}} = \frac{(7+\cos^2\theta^*)\sin^2\theta^*}{(3+\cos^2\theta^*)^2}, \quad A_{\mathsf{T}} = \frac{\sin^4\theta^*}{(3+\cos^2\theta^*)^2}.$$

$$\frac{A_{\mathsf{T}}(\theta^*)\cos(2\phi-\phi_1-\phi_2)}{A_{\mathsf{L}}(\theta^*)} = \frac{\sin^2\theta^*}{7+\cos^2\theta^*}\cos(2\phi-\phi_1-\phi_2),$$

4.2 Annihilation-in-Flight (AIF)

$(e^+e^- \to 2\gamma)$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathsf{AIF}} = \frac{\alpha^2(1+\cos^2\theta^*)}{s\sin^2\theta^*}\Big(\,1 + P_{\mathsf{L}}^1 P_{\mathsf{L}}^2 B_{\mathsf{L}}(\theta^*) + |\boldsymbol{P}_{\mathsf{T}}^1||\boldsymbol{P}_{\mathsf{T}}^2| B_{\mathsf{T}}(\theta^*)\cos(2\phi - \phi_1 - \phi_2)\,\Big)\,,$$

where

$$B_{\mathsf{L}}(\theta^*) = 1, \quad B_{\mathsf{T}}(\theta^*) = \frac{\sin^2\theta^*}{1+\cos^2\theta^*}.$$

$$\frac{B_{\mathsf{T}}(\theta^*)\cos(2\phi - \phi_1 - \phi_2)}{B_{\mathsf{L}}(\theta^*)} = \frac{\sin^2\theta^*}{1+\cos^2\theta^*}\cos(2\phi - \phi_1 - \phi_2),$$

5.1. Possibility of a new experiment @ J-PARC

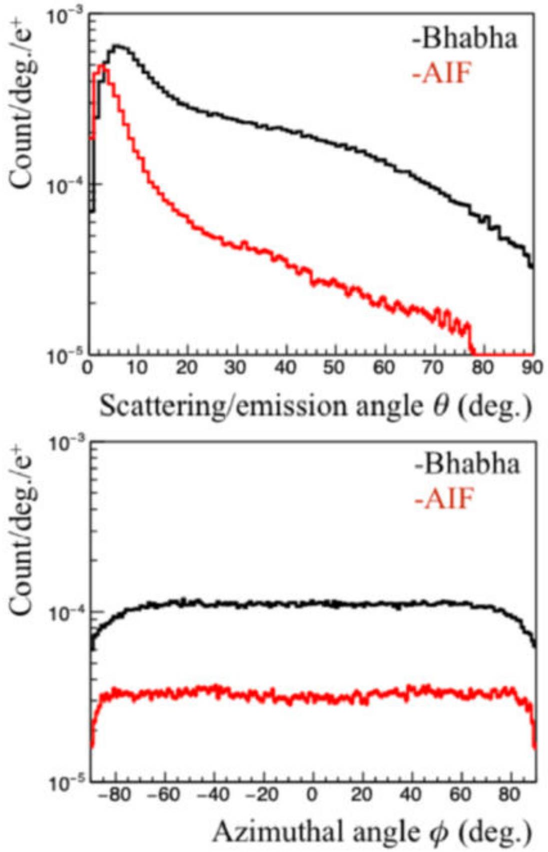
At Materials and Life Science Experimental Facility (MLF) Muon Science Establishment (MUSE), the world-highest intensity of pulsed muon beam has been established.

Precursor experiment at PSI (N.Danneberg et al., PRL **94**,021802)

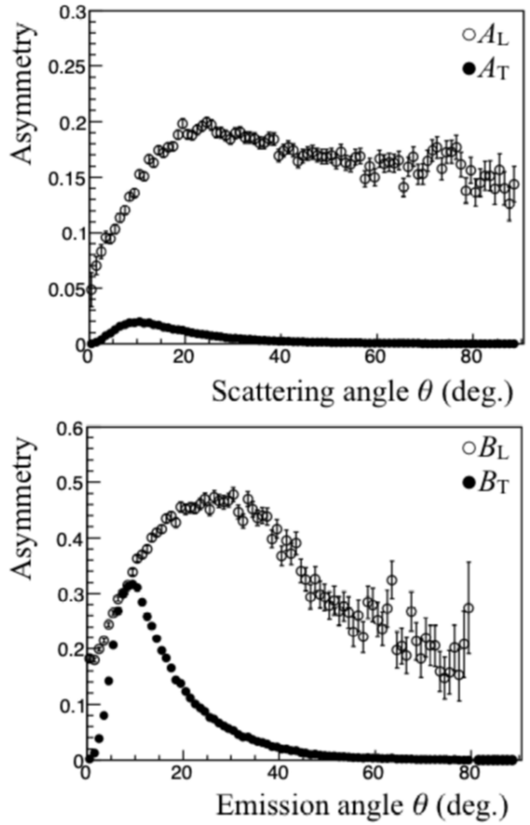
$$P_{\mathrm{T1}} = (6.3 \pm 7.7 \pm 3.4) \times 10^{-3},$$
$$P_{\mathrm{T2}} = (-3.7 \pm 7.7 \pm 3.4) \times 10^{-3},$$

Three major components: high-intensity pulsed muon beam at J-PARC, an electron-polarized scattering/annihilation target, and segmented positron and photon detectors.

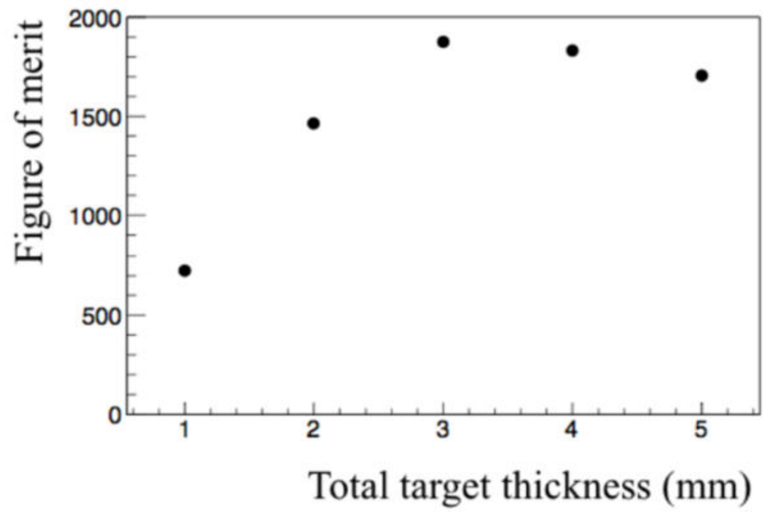
5.2. Simulation study



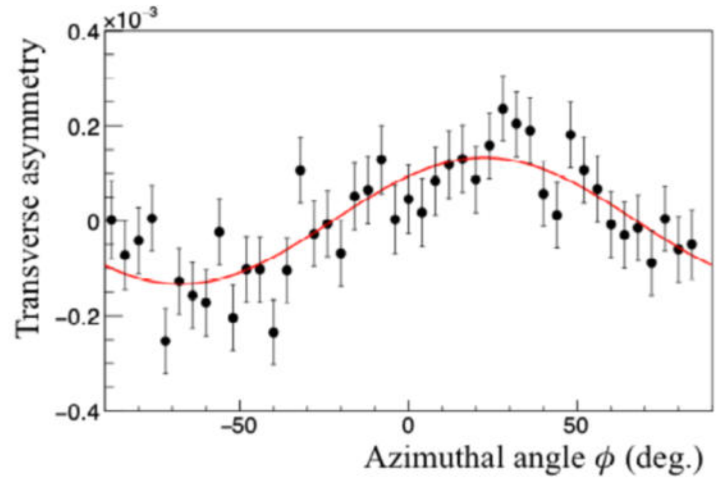
Simulated angular distributions of Bhabha scattering and AIF: (top) scattering/emission angle (θ); (bottom) azimuthal angle ϕ.



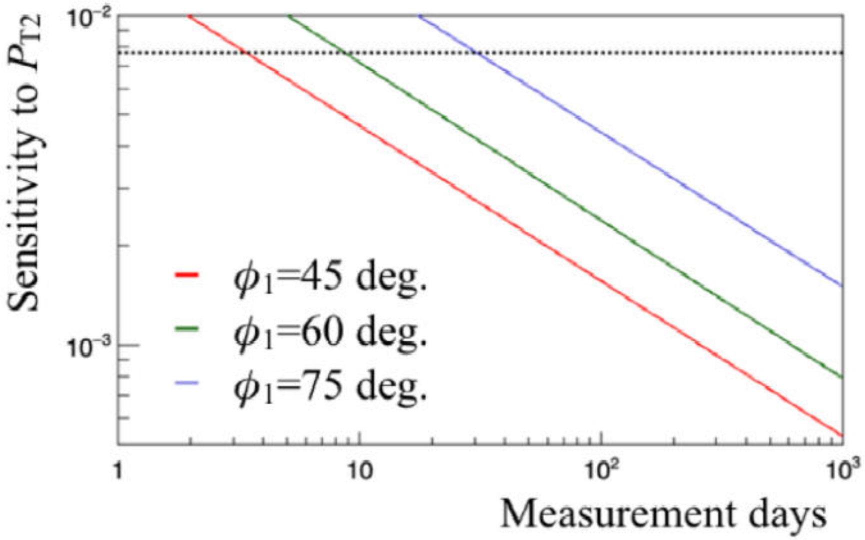
Simulated asymmetries with Bhabha scattering and AIF: (top) the result of Bhabha polarimeter case; (bottom) the result of AIF polarimeter case.



Calculated target thickness dependence of the FOM. At each target thickness, the energy thresholds and the emission angle acceptance are optimized to maximize the FOM. The number of simulated muons is 1×10^7 for each point.



Expected sensitivity to the transverse polarization using the AIF polarimeter for $\mathrm{P}_{T2} = 7.7 \times 10^{-3}$. $\phi_2 = 0$, ϕ_1 ia assumed $\pi/4$.. The oscillation amplitude obtained by the fiiting is $(1.5 \pm 0.2) \times 10^{-4}$.



Expected sensitivity to the transverse polarization using the AIF polarimeter. The abscissa represents the amount of time for $\sigma \geq 3$. The curves in each color correspond to the respective value of ϕ_1. The horizontal dotted line indicates the statistical uncertainty for P_{T1} and P_{T2} in the precursor measurement by Danneberg et al.

Can you conclude the Majoranality of neutrino if $T(e) \neq 0$?

Definitely Yes after we perform complementary checks which support this result, as any new theory does.

canonical seesaw

$$\mathcal{L}_N = -h_{ij}\overline{l_{L,i}}\phi N_j - \frac{1}{2}\sum_i \overline{N_i^C} M_i N_i + h.c.$$

$$m_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \qquad m_\nu = -m_D^T M_R^{-1} m_D$$

inverse seesaw

$$\mathcal{L} = -\bar{\nu}_L m_D N_R - \bar{S}_L M N_R - \frac{1}{2}\bar{S}_L \mu S_L^C + H.c,$$

$$M_\nu = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M^T \\ 0 & M & \mu \end{pmatrix} \qquad m_\nu = m_D^T (M^T)^{-1} \mu M^{-1} m_D$$

double suppression $\rightarrow$ low mass M_R (Large T-ood term)

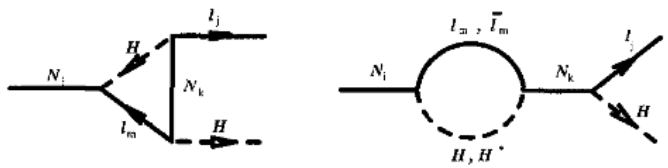
Baryogenesis via leptogenesis

$$Y_B \equiv \frac{n_B - n_{\overline{B}}}{s} = \frac{\epsilon}{g^*} \approx 0.6 \times 10^{-10}$$

$$\epsilon = \frac{1}{8\pi(h^\dagger h)_{11}} \sum_j \mathrm{Im}\left[(h^\dagger h)^2_{1j}\right] \left\{ f(M_j^2/M_1^2) + 2g(M_j^2/M_1^2) \right\}$$

$$f(x) \equiv \sqrt{x}\left[1 - (1+x)\ln\left(\frac{1+x}{x}\right)\right]$$

$$g(x) \equiv \frac{\sqrt{x}}{2(1-x)} ,$$



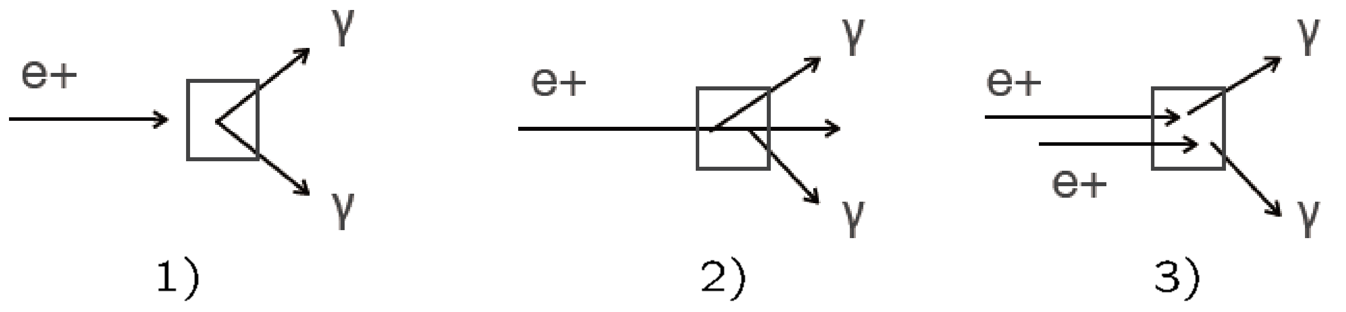
(a) (b)

Thus we may solve two major unsolved problems in particle physics, Majoranality of ν and Baryon Asymmetry in the Universe (BAU), simultaneouly.

Thanks for listening

Back up slides

- Background events:



1) AIF

2) Consequtive bremsstrahlungs by one positron.

3) Two positrons bremsstrahlung independently.

- Resolution effects:

  measurement accuracies on θ, ϕ, E.

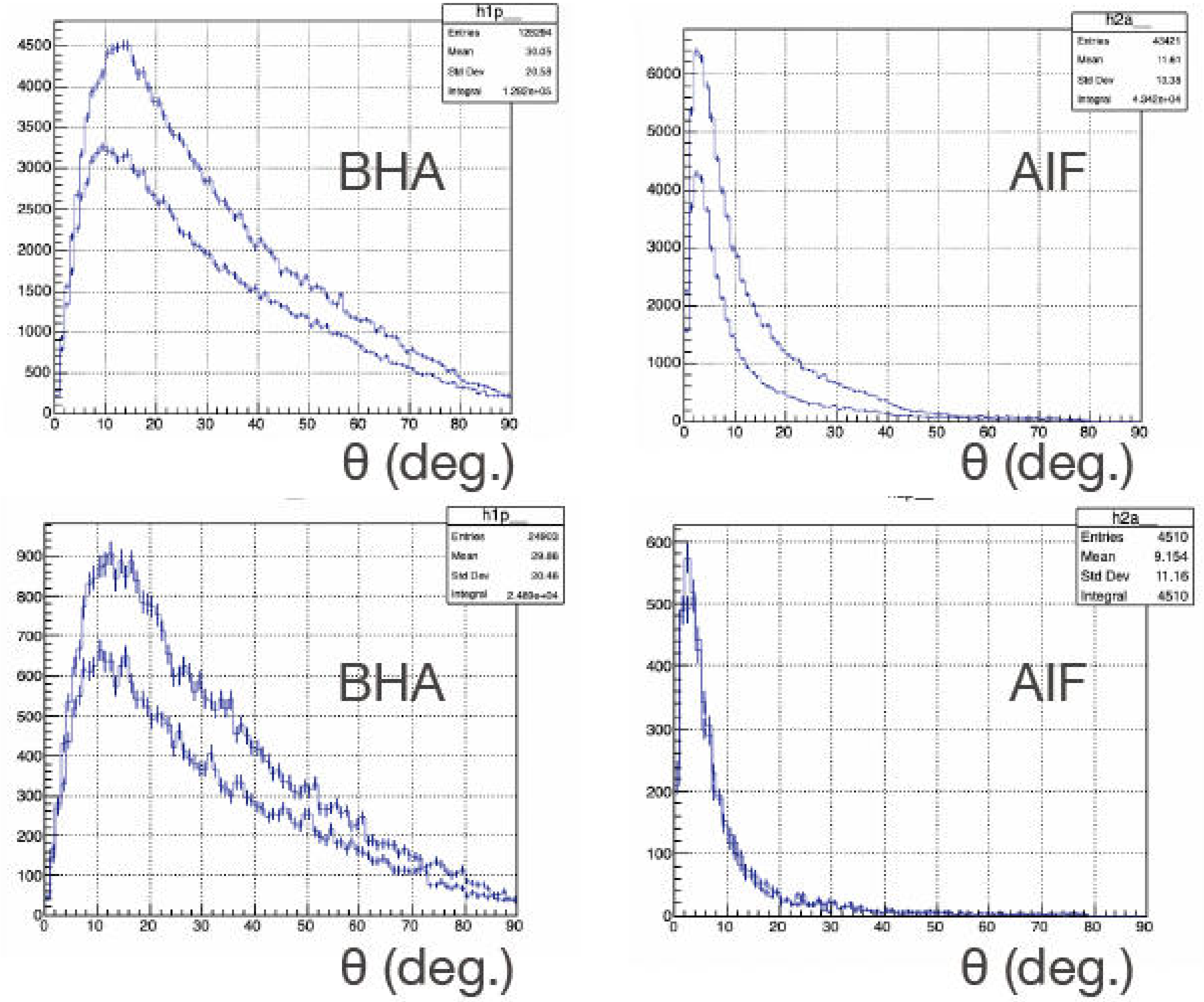
- Depolarization effects of beam (positron) and target (electron).

- 偏極陽電子

Bhabha散乱およびAIF事象候補をトラッカーとカロリメータの情報から選択しθをplotした図。

各パネルの2つのヒストグラムは標的の偏極方向(+, -)に対応する。

- 偏極電子



simulated by Kanda