Polarized electron target as tool for testing time reversal symmetry violation and neutrino nature in leptonic weak interactions at low energies

{ Wiesław Sobków and Arkadiusz Błaut}@ift.uni.wroc.pl
Institute of Theoretical Physics, University of Wrocław

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Introduction

- no difference between Dirac and Majorana neutrinos in Glashow-Salam-Weinberg model (GSW) [1] with V-A interaction (**left-handed chirality**) in relativistic limit
- no effects of time reversal symmetry violation (TRSV) in leptonic processes, e.g. neutrino-electron elastic scattering (NEES)
- single CP violating phase of CKM quark mixing matrix does not explain matter-antimatter asymmetry of universe (**new TRSV phases are required**)
- origin of parity violation is not clarified
- background problem in low energy neutrino experiments
- experimental results still leave space for non-standard complex S, T, P couplings of **right chiral neutrinos**
- new tools sensitive to interferences between V-A and S, T, P are needed to measure TRSV and distinguish between Dirac and Majorana neutrinos
- polarized electron target (PET) may shed some light on various open questions: precise measurement of background level in low energy solar neutrinos, TRSV, neutrino nature, neutrino magnetic moments, the flavor composition of (anti)neutrino beam, axions, spin-spin interaction in gravitation [2], [3], [4], [5],[6],[7],[8]

Assumptions

- detection process is elastic scattering of low energy neutrinos on polarized electrons of target: $\nu_e + e^- \rightarrow \nu_e + e^-$
- amplitude for Dirac neutrinos:

$$M^D_{\nu_e e^-} = \frac{G_F}{\sqrt{2}}\{(\overline{u}_{e'}\gamma^{\alpha}(c^L_V - c^L_A\gamma_5)u_e)(\overline{u}_{\nu_{e'}}\gamma_{\alpha}(1-\gamma_5)u_{\nu_e}) + c^R_S(\overline{u}_{e'}u_e)(\overline{u}_{\nu_{e'}}(1+\gamma_5)u_{\nu_e}) + c^L_S(\overline{u}_{e'}u_e)(\overline{u}_{\nu_{e'}}(1-\gamma_5)u_{\nu_e}) + \text{other interactions } c^R_V,\, c^R_A,\, c^{R,L}_P,\, c^{R,L}_T\} \quad (1)$$

- coupling constants are denoted respectively to the incoming ν_e of left- (L) and right-handed (R) chirality
- $c^{R,L}_S$, $c^{R,L}_P$, $c^{R,L}_T$ are complex numbers and $c^L_{S,T,P} = c^{*R}_{S,T,P}$
- amplitude for Majorana ν_es does not contain vector V and tensor T interactions
- incoming neutrino beam comes from (un)polarized source and is linear superposition of left chiral with right chiral states
- due to superposition transversal components of neutrino spin polarization may appear
- model-independent considerations for flavor eigenstates in limit of vanishing neutrino mass.

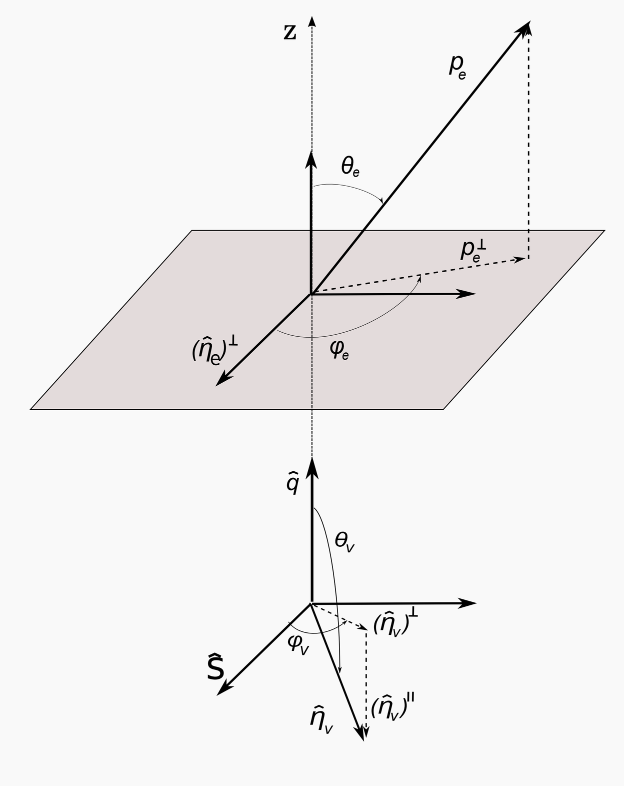

Fig. 1. Production plane of ν_e beam is spanned by polarization unit vector $\hat{\boldsymbol{S}}$ of source and ν_e LAB momentum unit vector $\hat{\mathbf{q}}$. Reaction plane is spanned by $\hat{\mathbf{q}}$ and transverse electron polarization vector of target $(\hat{\boldsymbol{\eta}}_{\boldsymbol{e}})^{\perp}$ (due to $\hat{\boldsymbol{\eta}}_{\boldsymbol{e}} \perp \hat{\mathbf{q}}$). θ_e is polar angle between $\hat{\mathbf{q}}$ and the unit vector $\hat{\mathbf{p}}_e$ of recoil electron momentum. ϕ_e is the angle between $(\hat{\boldsymbol{\eta}}_{\boldsymbol{e}})^{\perp}$ and the transversal component of outgoing electron momentum $(\hat{\mathbf{p}}_e)^{\perp}$.$\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} = (\sin\theta_\nu\,\cos\phi_\nu, \sin\theta_\nu\,\sin\phi_\nu, \cos\theta_\nu)$.

Results

standard V-A interaction with only L chiral neutrinos

left-right azimuthal asymmetry with asymmetry axis directed along $\Phi = \pi/2$

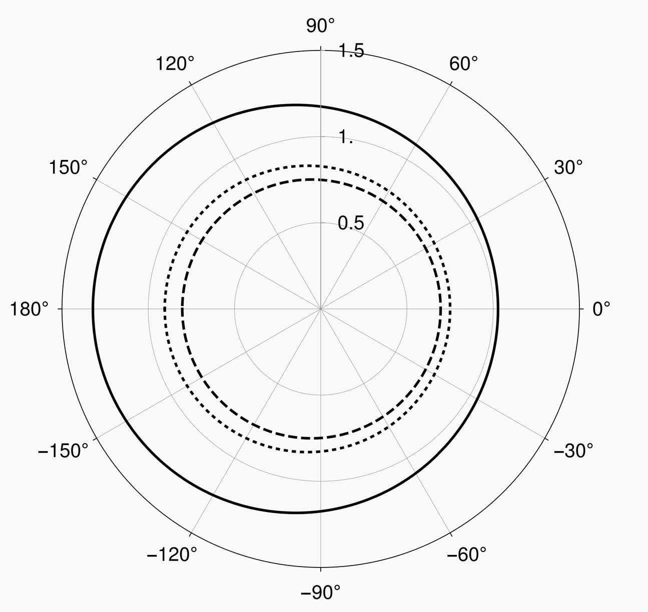

Fig. 2. Dependence of $d^2\sigma/d\phi_e d\theta_e$ on ϕ_e for $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = -1$, $E_\nu = 1\,MeV$: $\theta_e = \pi/12$ (dotted line), $\theta_e = \pi/6$ (solid line), $\theta_e = \pi/3$ (dashed line)

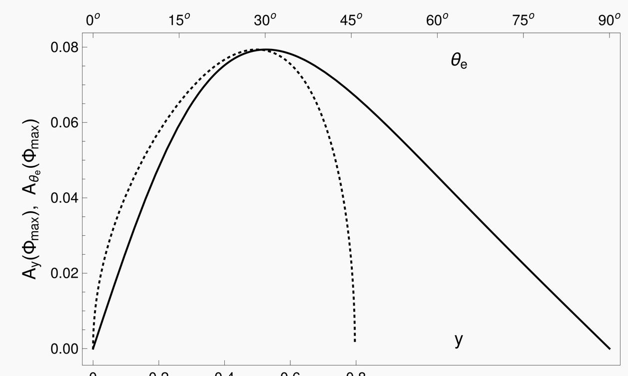

Fig. 3. $A_y(\Phi) := \dfrac{\int_{\Phi}^{\Phi+\pi} \frac{d^2\sigma}{d\phi_e dy}\, d\phi_e - \int_{\Phi+\pi}^{\Phi+2\pi} \frac{d^2\sigma}{d\phi_e dy}\, d\phi_e}{\int_{\Phi}^{\Phi+\pi} \frac{d^2\sigma}{d\phi_e dy}\, d\phi_e + \int_{\Phi+\pi}^{\Phi+2\pi} \frac{d^2\sigma}{d\phi_e dy}\, d\phi_e}$.

$$A_{\theta_e}(\Phi) := \frac{\int_{\Phi}^{\Phi+\pi} \frac{d^2\sigma}{d\phi_e d\theta_e}\, d\phi_e - \int_{\Phi+\pi}^{\Phi+2\pi} \frac{d^2\sigma}{d\phi_e d\theta_e}\, d\phi_e}{\int_{\Phi}^{\Phi+\pi} \frac{d^2\sigma}{d\phi_e d\theta_e}\, d\phi_e + \int_{\Phi+\pi}^{\Phi+2\pi} \frac{d^2\sigma}{d\phi_e d\theta_e}\, d\phi_e}$$

Plot of $A_y(\Phi = \pi/2)$ as a function y (dotted line) and $A_{\theta_e}(\Phi = \pi/2)$ as a function of θ_e (solid line) for $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = -1$, $E_\nu = 1\,MeV$.

possibility of TRSV for scenario with V-A, S and T interactions; asymmetry axis location Φ_{max} (upper plot in Fig.4, dashed line) and value of asymmetry $A(\Phi_{max})$ (lower plot in Fig.4, dashed line) may change for Dirac neutrinos when $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = -1$

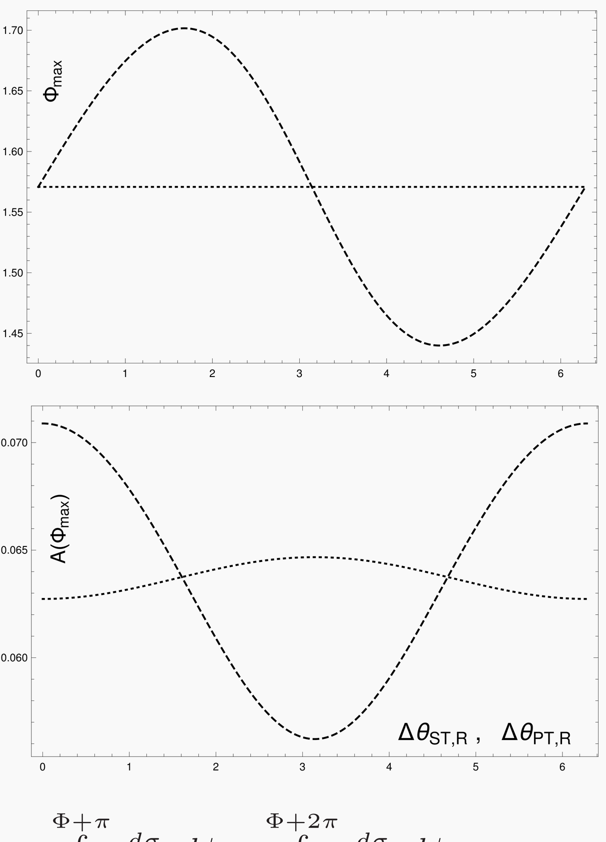

Fig. 4. $A(\Phi) := \dfrac{\int_{\Phi}^{\Phi+\pi} \frac{d\sigma}{d\phi_e}\, d\phi_e - \int_{\Phi+\pi}^{\Phi+2\pi} \frac{d\sigma}{d\phi_e}\, d\phi_e}{\int_{\Phi}^{\Phi+\pi} \frac{d\sigma}{d\phi_e}\, d\phi_e + \int_{\Phi+\pi}^{\Phi+2\pi} \frac{d\sigma}{d\phi_e}\, d\phi_e}$

Upper plot: dependence of Φ_{max} on $\Delta\theta_{ST,R}$ for $\theta_\nu = \pi, E_\nu = 1\,MeV$ in case of $V-A$ with S_R and T_R when $|c^R_S| = |c^R_T| = 0.2$ (dashed line); plot of Φ_{max} on $\Delta\theta_{PT,R}$ for $\theta_\nu = \pi, E_\nu = 1\,MeV$ in presence of $V-A$, P_R and T_R when $|c^R_P| = |c^R_T| = 0.2$ (dotted line). Lower plot: dependence of $A(\Phi_{max})$ on $\Delta\theta_{ST,R}$ (dashed line) and on $\Delta\theta_{PT,R}$ (dotted line), respectively, with same assumptions as for Φ_{max}.

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Recoil electrons azimuthal asymmetry

superposition L chiral with R chiral neutrinos

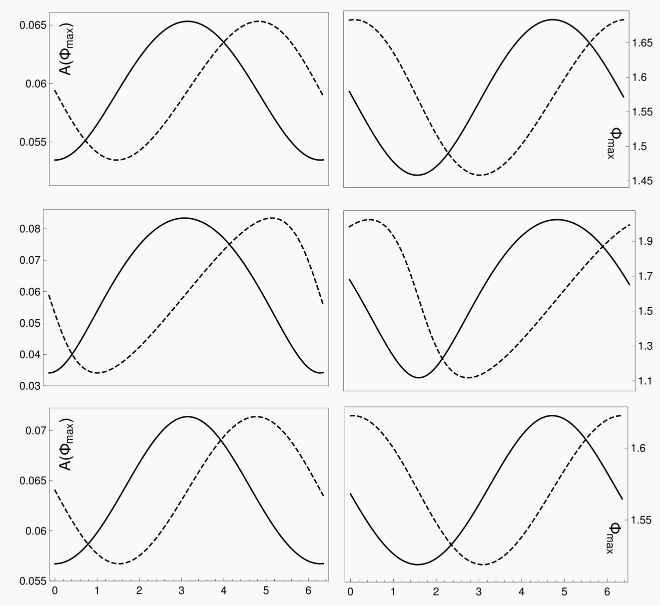

Fig. 5. Dependence of $A(\Phi_{max})$ on ϕ_ν (solid line) and Φ_{max} on ϕ_ν (dashed line), for $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = -0.95, E_\nu = 1\,MeV$. TRSC: upper left plot for case of $V-A$ and S_R when $|c^R_S| = 0.2, \theta_{S,R} = 0$; middle left plot for the combination of $V-A$ with T_R when $|c^R_T| = 0.2, \theta_{T,R} = 0$; lower left plot for Majorana case of $V-A$ with S_R when $|c^R_S| = 0.2, \theta_{S,R} = 0$. TRSV: upper right plot for the scenario with $V-A$ and S_R when $|c^R_S| = 0.2, \theta_{S,R} = \pi/2$; middle right plot for the case of $V-A$ and T_R when $|c^R_T| = 0.2, \theta_{T,R} = \pi/2$; lower right plot for Majorana case of $V-A$ with S_R when $|cS^R| = 0.2, \theta_{S,R} = \pi/2$

Spectrum of recoil electrons

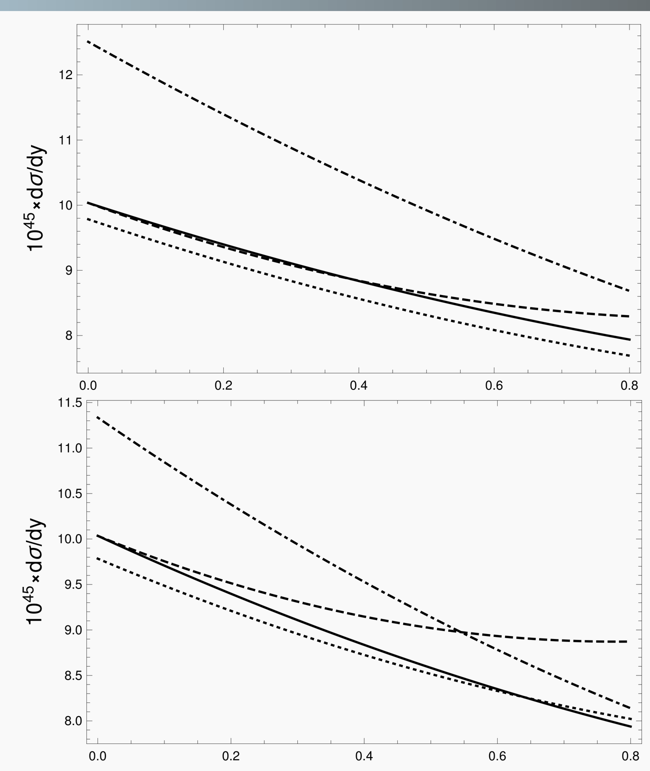

Fig. 6. Dependence of $d\sigma/dy$ on y for $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = -0.95, E_\nu = 1\,MeV$, $\phi_\nu = 0$. Upper plot for TRSC: standard $V-A$ interaction (solid line); the combination of $V-A$ and T_R when $|c^R_T| = 0.3, \theta_{T,R} = 0$ (dashed-dotted line); the case of $V-A$ and S_R when $|c^R_S| = 0.3, \theta_{S,R} = 0$ (dotted line); Majorana ν for $V-A$ with S_R when $|c^R_S| = 0.3, \theta_{S,R} = 0$ (dashed line). Lower plot for TRSV: standard $V-A$ interaction (solid line); the combination of $V-A$ and T_R when $|c^R_T| = 0.3, \theta_{T,R} = \pi/2$ (dashed-dotted line); the case of $V-A$ and S_R when $|c^R_S| = 0.3, \theta_{S,R} = \pi/2$ (dotted line); Majorana ν for $V-A$ with S_R when $|c^R_S| = 0.3, \theta_{S,R} = \pi/2$ (dashed line)

Polar distribution of recoil electrons

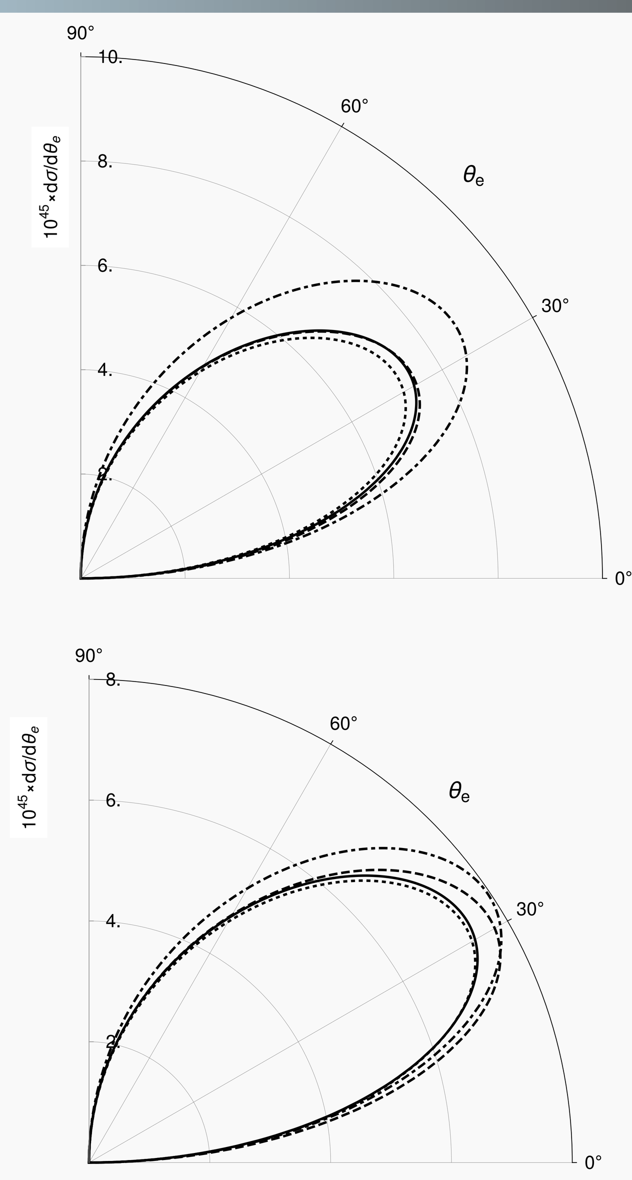

Fig. 7 Dependence of $d\sigma/d\theta_e = (d\sigma/dy)\,(dy/d\theta_e)$ as a function of θ_e for $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = -0.95$, $E_\nu = 1\,MeV$, $\phi_\nu = 0$. Upper plot for TRSC: standard $V-A$ interaction (solid line); the combination of $V-A$ and T_R when $|c^R_T| = 0.3, \theta_{T,R} = 0$ (dashed-dotted line); the case of $V-A$ and S_R when $|c^R_S| = 0.3, \theta_{S,R} = 0$ (dotted line); Majorana ν for $V-A$ with S_R when $|c^R_S| = 0.3, \theta_{S,R} = 0$ (dashed line). Lower plot for TRSV: standard $V-A$ interaction (solid line); the combination of $V-A$ and T_R when $|c^R_T| = 0.3, \theta_{T,R} = \pi/2$ (dashed-dotted line); the case of $V-A$ and S_R when $|c^R_S| = 0.3, \theta_{S,R} = \pi/2$ (dotted line); Majorana ν for $V-A$ with S_R when $|c^R_S| = 0.3, \theta_{S,R} = \pi/2$ (dashed line)

Conclusions

Azimuthal asymmetry and other observables contain interferences between $V-A$ and exotic S_R, P_R, T_R couplings proportional to $(\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}})^{\perp}$ related to production process (superposition of L- with R chiral states). It allows to search for TRSV and distinguish between Dirac and Majorana ν_es. When incoming ν_es are Dirac purely L chiral fermions, but S, T interactions participate, then azimuthal asymmetry is also sensitive to TRSV. Proper tests require intense low-energy ν_e sources, PET, and detectors sensitive to azimuthal angle and polar angle of scattered electrons with good angular resolution. Detectors measuring recoil electron spectrum should be constructed from magnetic materials and scintillating media (feasibility of electron polarized scintillating GSO target has been confirmed by [9]).