Academic Progress:

- Comprehensive: Passed (Aug 2022)
- Class: PHYS 504 (Nuclear Physics): C+)
- Class: PHYS 502 (Cond. Matt. Physics): TBD)

Recoil Asymmetry in Polarized ^{37}K

James McNeil[1,3], Alexandre Gorelov[3], Dan Melconian[2], John Behr[1,3]

Department of Physics and Astronomy, University of British Columbia[1],
Department of Physics and Astronomy, Texas A&M [2]
TRIUMF[3]
Funding: NSERC,DOE

Outline:

- Introduction
- Theory
- TRINAT ^{37}K experiment
- MC Simulation

Introduction:

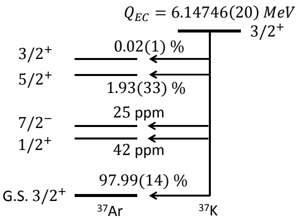
- Lee and Yang[1] formulation of weak decay H_{int} includes Lorentz **V**ector, **A**xial-Vector, **S**calar, **T**ensor, **P**seudo-scalar couplings $(C_V, C_A, C_S, C_T, C_P)$
- Standard Model weak decay $V - A$
- Charged weak decay mediated by massive ~ 80 GeV W-boson wrt momentum transfer (4-point contact interaction)

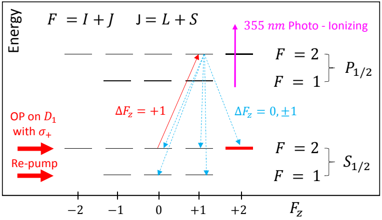
$$
\begin{aligned}
H_{int} = & (\bar{\psi}_p \psi_n)(C_S \bar{\psi}_e \psi_\nu + C'_S \bar{\psi}_e \gamma_5 \psi_\nu) + \\
& + (\bar{\psi}_p \gamma_\mu \psi_n)(C_V \bar{\psi}_e \gamma_\mu \psi_\nu + C'_V \bar{\psi}_e \gamma_\mu \gamma_5 \psi_\nu) + \\
& + \frac{1}{2}(\bar{\psi}_p \sigma_{\lambda\mu} \psi_n)(C_T \bar{\psi}_e \sigma_{\lambda\mu} \psi_\nu + C'_T \bar{\psi}_e \sigma_{\lambda\mu} \gamma_5 \psi_\nu) + \\
& - (\bar{\psi}_p \gamma_\mu \gamma_5 \psi_n)(C_A \bar{\psi}_e \gamma_\mu \gamma_5 \psi_\nu + C'_A \bar{\psi}_e \gamma_\mu \psi_\nu) + \\
& + (\bar{\psi}_p \gamma_5 \psi_n)(C_P \bar{\psi}_e \gamma_5 \psi_\nu + C'_P \bar{\psi}_e \psi_\nu) + H.C.
\end{aligned}
$$

$$
H_{int}^{SM} = [\bar{\psi}_p (C_V \gamma_\mu - C_A \gamma_\mu \gamma_5) \psi_n] \times [\bar{\psi}_e (\gamma_\mu - \gamma_\mu \gamma_5) \psi_\nu]
$$

- Time reversal invariance $C = C'$
- Parity violation maximal (Wu[2] ^{60}Co, and many more accurate exp.) from C_A $\rightarrow$ SM neutrinos chiral left-handed
- Jackson, Treiman, and Wyld[2] (JTW) formulated probability density from H_{int} in oriented nuclei assuming $C_P = 0$

[1] T.D. Lee and C.N. Yang, Phys. Rev. 104, 254 (1956); [2] C.S. Wu, E.Ambler, R.W. Hayward, D.D. Hoppes, R.P. Hudson, Phys. Rev. 105, 1413 (1957)
[3] J.D Jackson, S.B. Treiman, H.W. Wyld, Phys. Rev. 106(3) (1957)





(left) Decay Scheme of ^{37}K. (right) Optical pumping the nuclear spin using the hyperfine interaction through biased random walk into the $|F=2, F_z=+2\rangle$ stretched/polarized state for σ_+.

$$dN = W(\vec{P}, \vec{p}_e, \vec{p}_r)d^3p_e d^3p_r = F(Z, E_e)d^3p_e d^3p_r \delta(E_o - E_e - E_\nu)\xi \times$$
$$\left\{1 + \frac{bm}{E_e} + a_{\beta\nu}\frac{\vec{p}_e\vec{p}_\nu}{E_e E_\nu} + c'\left[\frac{\vec{p}_e\vec{p}_\nu}{3E_e E_\nu} - \frac{(\vec{p}_e\hat{P})(\vec{p}_\nu\hat{P})}{E_e E_\nu}\right] + \vec{P}\left[A_\beta\frac{\vec{p}_e}{E_e} + (B_\nu + \frac{\delta B_\nu m}{E_e})\frac{\vec{p}_\nu}{E_\nu}\right]\right\}$$

- Keep $\frac{m}{E_e}$ terms (neglect $\alpha\frac{m}{p_e} \rightarrow O(Im(C_S, C_T))$)
- b Fierz, δB_ν *linear* in $x, y = \frac{C_S}{C_V}, \frac{C_T}{C_A}$ at $O(C_S, C_T)$

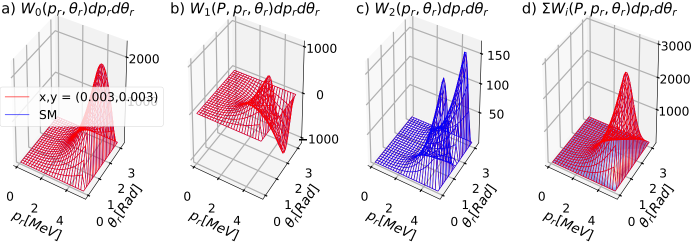
$$b = \pm\gamma(x + \rho^2 y)/(1+\rho^2) \quad : \rho = \eta\frac{C_A M_{GT}}{C_V M_F}$$
$$\delta B_\nu = \frac{\mp\gamma\rho}{1+\rho^2}\left[\delta_{JJ'}\sqrt{\frac{J}{J+1}}x \mp \left[\rho\lambda_{JJ'} \mp \delta_{JJ'}\sqrt{\frac{J}{J+1}}\right]y\right]$$

→ **Why** $^{37}_{19}K$?

- Mirror nuclei GS. sym $|p> \leftrightarrow |n>$
- Large 98% GS branch $J^\pi : \frac{3^+}{2} \rightarrow \frac{3^+}{2}$
- OP on $D1$ to polarize P nuclear spin
- Non-distructive UV probe to measure $P = 0.9913(8)$ (Fenker)[1].

[1] B. Fenker, et al, New J. Phys. 18 073028 (2016)

Recoil Probability Density Distributions

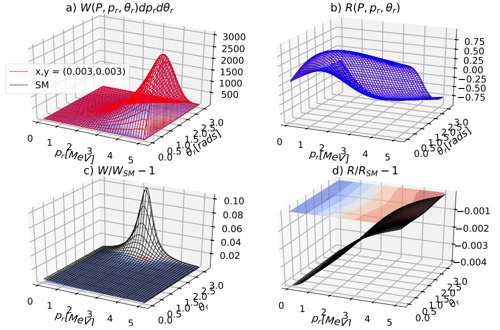


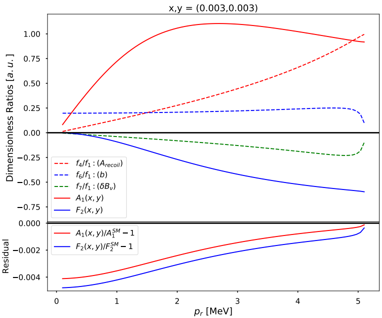
a),b),c) showing the order $i = 0, 1, 2$ term $W_i(P, p_r, \cos^i(\theta_r)\sin(\theta_r))dp_r d\theta_r$ distributions, correctly scaled with respect to each other for $x, y = 0.003$ (red), and $x, y = 0$ SM (blue). Their sum is shown in d), demonstrating the dominance of the $i = 0, 1$ contributions.

$$dN = dp_r d\theta_r \{f_1(p_r) - \left[a_{\beta\nu} + \frac{c'}{3}\right] f_2(p_r) + c' f_3(p_r) + PA_r f_4(p_r)\cos\theta_r + c' f_5(p_r)\cos^2\theta_r + b f_6(p_r) + P\delta B_\nu f_7(p_r)\cos\theta_r\}\xi\sin\theta_r \quad ; \quad A_r = -(A_\beta + B_\nu) \sim \delta_{JJ'}$$

- Analytic solution dN with Fermi function $F(Z, E_e) = 1$, and neglecting recoil order effects ($< 400\ eV$)
- 98% GS branch $3/2^+ \rightarrow 3/2^+$ $(A_r > 0)$
- 2% ExS branch $3/2^+ \rightarrow 5/2^+$ $(A_r = 0)$
- Excited state systematics in A_r begin at 0.02% $3/2^+ \rightarrow 3/2^+$ branch

- Polynomial functions $f_j(p_r)$
- Diminishing $\cos^i(\theta_r)\sin(\theta_r)$ weighting in $dN_i = W_i dp_r d_{\theta_r}$ with order $i = 0, 1, 2$
- Dominant order $i = 0$ enhances sensitivity to x, y via b Fierz term
- Consider dominant GS decay



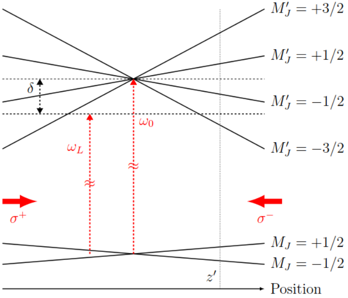


(left) a) $W(P, p_r, \theta_r)dp_r d\theta_r$ distribution, and b) corresponding $\mathcal{R}(P, p_r, \theta_r)$ for $x, y = 0.003$ (red), and SM $x, y = 0$ (blue). The corresponding SM deviations in $W dp_r d\theta_r$, and $\mathcal{R}$ are shown in c),d), respectively. It is assumed that $P_+ = -P_- = P$. (right) Recoil momentum p_r dependence of $f_j(p_r)/f_1(p_r)$. Since $\mathcal{R}(P, p_r, \theta_r)$ is measured the parameters to fit for are $A_1[p_r]$, and possibly $F_2[p_r]$, which are plotted as an example assuming $x, y = 0.003$. The bottom plot shows the SM($x, y = 0$) deviation of $A_1[p_r]$, and $F_2[p_r]$.

$$\mathcal{R}(P, p_r, \theta_r) = \frac{dN(P_+) - dN(P_-)}{dN(P_+) + dN(P_-)} = \frac{P A_1[p_r] \cos\theta_r}{1 + c' F_2[p_r] \cos^2\theta_r}$$

- Notable SM dev. in $W dp_r d\theta_r$ for $x, y = 0.003$
- Super-ratio $\mathcal{R}(P, p_r, \theta_r)$ aids in canceling some systematics (e.g. rMCP ion impact angle wrt channel axis)

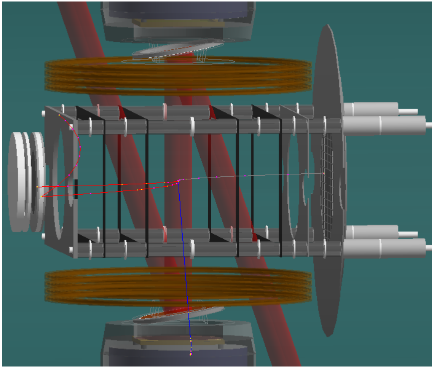
- $A_1[p_r] = A_1[A_r^{SM}, \delta B_\nu, b, p_r]$
- $F_2[p_r] = F_2[b, p_r]$
- $c' = cT \sim -0.32$ weighting rel. small



MOT D2 ($4S_{1/2} \rightarrow 4P_{3/2}$) doppler limited cooling (Fenker[1])

- Magneto-Optic-Trap (MOT) cools and confines $\sim 10k$ ^{37}K atoms at mK in $< 1mm^3$
  $\rightarrow$ Zeeman split D2 transition sublevels
  $\rightarrow$ Cent force for $r > 0$ from σ^+ *or*, σ^- trans.
- Recoiling ^{37}K ion position/TOF in coincidence with $\beta^-(E + dE)$, and/or atomic shake-off-e^-
- Electrostatic Hoops at 1kV/cm separate recoil charge states in TOF. Recoil ions and SOE's are detected with opposing MCP's.

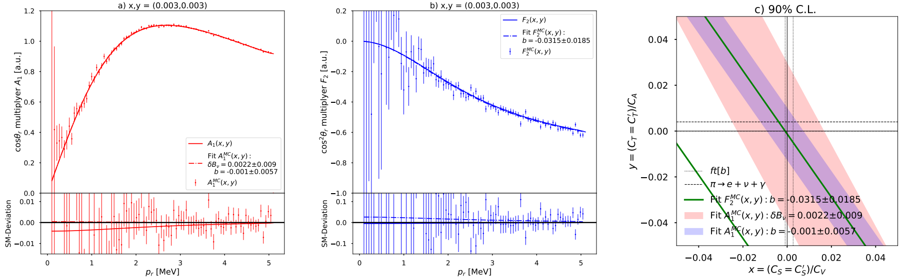
- Upgraded pellicle mirrors (70 nm Au, 4 um Kapton)[2] to reduce scattering before $E + \Delta E$
- Upgraded eMCP (funnel $\sim 90\%$ eff.) & WSZ detector for position readout
  $\rightarrow$ Need eMCP + rMCP delayed coinc.
  $\rightarrow$ Want $\uparrow$ res. w/ active DC subtraction



β-decay of ^{37}K with recoiling ^{37}Ar daughter ion (gray), β^+ (blue) and Shake-Off-Electrons (red) at TRINAT.

[1] Ben Fenker PhD thesis; [2] Stern Family of National Photocolor Corp.

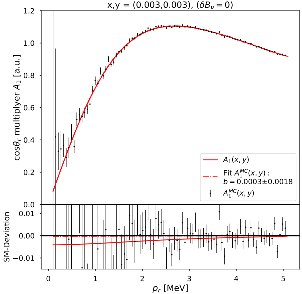
MC Simulation

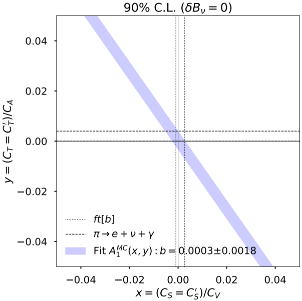


MC generated $\mathcal{R}(P, p_r, \theta_r)$ ($\sim 30M$ events) assuming $x, y = 0.003$ fit over θ_r to extract a) $A_1[p_r]$, and b) $F_2[p_r]$ with indicated constraints on δB_ν, and b Fierz. The 90% C.L. on Lorentz scalar and tensor couplings x, y are shown in c) for the indicated constraints from δB_ν, and b Fierz in (a,b), with overlayed limits from $\pi \to e + \nu + \gamma$[1], and super-allowed $0^+ \to 0^+$ Ft values[2].

- 5 day run with $10k$ atoms trapped $\to 45M$ recoil-SOE in each $P_\pm$ states
- Fit $\mathcal{R}(P, p_r, \theta_r)$ on θ_r to simultaneously extract $PA_1[p_r]$ and $c'F_2[p_r]$
- Fit $A_1[p_r]$, & $F_2[p_r]$ floating δb_ν, & b Fierz
- Even with a conservative 30M recoil-SOE coincident events unlikely to have sufficient stats to compete with existing constraints.
- Can we reduce dimensionality of fit to improve constraints? Systematics?

[1] F. Wauters, A. Garcia, and R. Hong, Phys. Rev. C 89 025501 (2014); [2] M. Dunlop, et al, Phys. Rev. Lett. 116 172501 (2016)





MC generated $\mathcal{R}(P, p_r, \theta_r)$ ($\sim 30M$ events) assuming $x, y = 0.003$ fit over θ_r to extract (left-plot) $A_1[p_r]$ and $F_2[p_r]$. $A_1[p_r]$ is fit assuming dominant sensitivity via b Fierz and setting $\delta B_\nu = 0$. The 90% C.L. on Lorentz scalar and tensor couplings x, y are shown in (right-plot) and is competitive with limits from $\pi \to e + \nu + \gamma$[1], and super-allowed $0^+ \to 0^+$ Ft values [2].

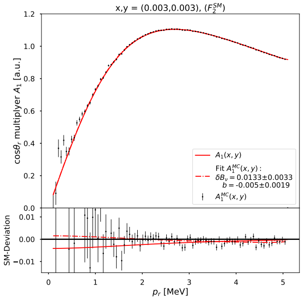
- Dominant sensitivity to x, y via b Fierz as above
- Fit $\mathcal{R}(P, p_r, \theta_r)$ on θ_r to simultaneously extract $PA_1[p_r]$ and $c'F_2[p_r]$
- Fit $A_1[p_r]$, floating b Fierz assuming $(\delta B_\nu = 0)$
- Fit systematics in x, y bounds are small!
- Already competitive constraints to $\pi \to e + \nu + \gamma$, and super-allowed $0^+ \to 0^+$ Ft values

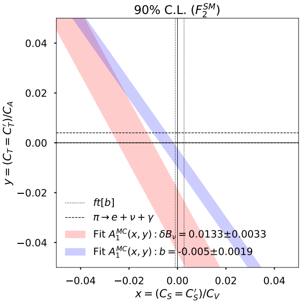
Conclusion: Competitive sensitivity to Lorentz Scalar and Tensor x, y couplings can be achieved if we can show systematics are small from fits to $A_1[p_r]$ for b Fierz assuming $\delta B_\nu = 0$

References

- T.D. Lee and C.N. Yang, Phys. Rev. 104, 254 (1956)
- O. Kofoed-Hansen, Dan. Mat. Fys., 28(9), (1954)
- C.S. Wu, E.Ambler, R.W. Hayward, D.D. Hoppes, R.P. Hudson, Phys. Rev. 105, 1413 (1957)
- J.D Jackson, S.B. Treiman, H.W. Wyld, Phys. Rev. 106(3) (1957)
- J.D Jackson, S.B. Treiman, H.W. Wyld, Nuclear Physics 4, 206-212 (1957)
- F. Wauters, A. Garcia, and R. Hong, Phys. Rev. C 89 025501 (2014)
- M. Dunlop, et al, Phys. Rev. Lett. 116 172501 (2016)
- B. Fenker, et al, New J. Phys. 18 073028 (2016)
- B. Fenker PhD thesis, https://oaktrust.library.tamu.edu/handle/1969.1/158988
- J.R.A. Pitcairn, et al, Phys. Rev. C 79, 015501 (2009)
- J.C. Hardy and I.S. Towner, Phys. Rev. C, 91, 025501 (2015)

MC Simulation (F_2^{SM})





MC generated $\mathcal{R}(P, p_r, \theta_r)$ ($\sim 30M$ events) assuming $x, y = 0.003$ fit over θ_r to extract (left-plot) $A_1[p_r]$ assuming the SM value of $F_2[p_r]$ given that c' is small. Constraints on δB_ν and b Fierz are shown from fits to $A_1[p_r]$. The 90% C.L. on Lorentz scalar and tensor couplings x, y are shown in (right-plot) and is competitive with limits from $\pi \to e + \nu + \gamma$[1], and super-allowed $0^+ \to 0^+$ Ft values[2].

- Since c' reasonably small, assume SM value of $F_2[p_r]$
- Fit $\mathcal{R}(P, p_r, \theta_r)$ on θ_r to extract $PA_1[p_r]$
- Fit $A_1[p_r]$, floating δb_ν, & b Fierz
- Fit systematics in x, y bounds are considerable! Can't assume F_2^{SM}

[1] F. Wauters, A. Garcia, and R. Hong, Phys. Rev. C 89 025501 (2014); [2] M. Dunlop, et al, Phys. Rev. Lett. 116 172501 (2016)

Appendix

- Recoil momentum polynomial weighting functions $f_j[p_r]$

$$
\begin{aligned}
f_1 &= p_r^2(1+p_r^2-E_o^2)^2[3E_o^4+E_o^2(3-4p_r^2)+p_r^4+p_r^2]/12(E_o^2-p_r^2)^3\\
f_2 &= p_r^2(1+p_r^2-E_o^2)^2[3E_o^4-E_o^2(8p_r^2+3)+p_r^2(5p_r^2-1)]/6(E_o^2-p_r^2)^3\\
f_3 &= -p_r^2(1+p_r^2-E_o^2)^3/12(E_o^2-p_r^2)^2\\
f_4 &= E_o p_r^3(E_o^2-p_r^2+2)(1+p_r^2-E_o^2)^2/6(E_o^2-p_r^2)^3\\
f_5 &= -p_r^4(E_o^2-p_r^2+2)(1+p_r^2-E_o^2)^2/6(E_o^2-p_r^2)^3\\
f_6 &= E_o p_r^2(1+p_r^2-E_o^2)^2/2(E_o^2-p_r^2)^2\\
f_7 &= -p_r^3(1+p_r^2-E_o^2)^2/2(E_o^2-p_r^2)^2.
\end{aligned}
$$

- Measured observables $A_1[p_r]$ and $F_2[p_r]$

$$
\begin{aligned}
A_1[p_r] &= [A_r^{SM} f_4(p_r) + \delta B_\nu f_7(p_r)] \cdot F_2[p_r]/f_5(p_r)\\
F_2[p_r] &= f_5(p_r)/\left(f_1(p_r) + b f_6(p_r) - \left[a_{\beta\nu} + \frac{c'}{3}\right] f_2(p_r) + c' f_3(p_r)\right).
\end{aligned}
\tag{1}
$$