The TRINAT Trap Program

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Outline

Limit on Scalar Interaction
Upgraded Experiment and Projected Precision

Limit on Right-Handed Currents
Upgraded Experiment and Projected Precision

Limit on Tensor Interaction
Upgraded Experiment and Projected Precision

β-decay rate (Jackson, Treiman, Wyld 1957):

$$dW =$$

$$dW_o(1 + \frac{\vec{p_\beta} \cdot \vec{p_\nu}}{E_\beta E_\nu} a_{\beta\nu} + \frac{\Gamma m_e}{E_\beta} b + \frac{\vec{J}}{J} \cdot [\frac{\vec{p_\beta}}{E_\beta} A_\beta + \frac{\vec{p_\nu}}{E_\nu} B_\nu + \frac{\vec{p_\beta} \times \vec{p_\nu}}{E_\beta E_\nu} D]$$

$$+c[\frac{\vec{p_\beta} \cdot \vec{p_\nu}}{3E_\beta E_\nu} - \frac{(\vec{p_\beta} \cdot \vec{j})(\vec{p_\nu} \cdot \vec{j})}{E_\beta E_\nu}][\frac{J(J+1) - 3 < (\vec{J} \cdot \vec{j})^2 >}{J(2J-1)}])$$

Allows for: V - A, Scalar, Tensor Interactions

Left, Right-handed currents

Time-reversal violation

$a_{\beta\nu},\ b,\ c,\ A_\beta,\ B_\nu,\ D$: values predicted by the Standard Model

Recent review: S. Severijins and M. Beck, Rev. Mod. Phys. 78 991 (2006)

Measurements feasible using Atom traps and Radioactive Beams.

Limits on Scalar Boson Interaction

$$dW =$$

$$dW_o(1 + \frac{\vec{p_\beta} \cdot \vec{p_\nu}}{E_\beta E_\nu} a_{\beta\nu} + \frac{m_e}{E_\beta} b + \frac{\vec{J}}{J} \cdot [\frac{\vec{p_\beta}}{E_\beta} A_\beta + \frac{\vec{p_\nu}}{E_\nu} B_\nu + \frac{\vec{p_\beta} \times \vec{p_\nu}}{E_\beta E_\nu} D]$$

$$+c[\frac{\vec{p_\beta} \cdot \vec{p_\nu}}{3E_\beta E_\nu} - \frac{(\vec{p_\beta} \cdot \vec{j})(\vec{p_\nu} \cdot \vec{j})}{E_\beta E_\nu}][\frac{J(J+1) - 3 < (\vec{J} \cdot \vec{j})^2 >}{J(2J-1)}])$$

For pure Fermi $0^+ \rightarrow 0^+$ decay $\beta - \nu$ angular correlation:

$$P(\theta) = 1 + b\frac{\mathrm{m}_\beta}{\mathrm{E}_\beta} + a_{\beta\nu}\frac{\mathrm{v}_\beta}{\mathrm{c}} cos(\theta)$$

$$a_{\beta\nu} = 1 - 4\frac{g_S^2}{g_V^2}\left(|a_L^S|^2 + |a_R^S|^2\right) \qquad b = \pm\frac{g_S}{g_V}\frac{\mathcal{R}e(a_{LL}a_R^S)}{|a_{LL}|^2}$$

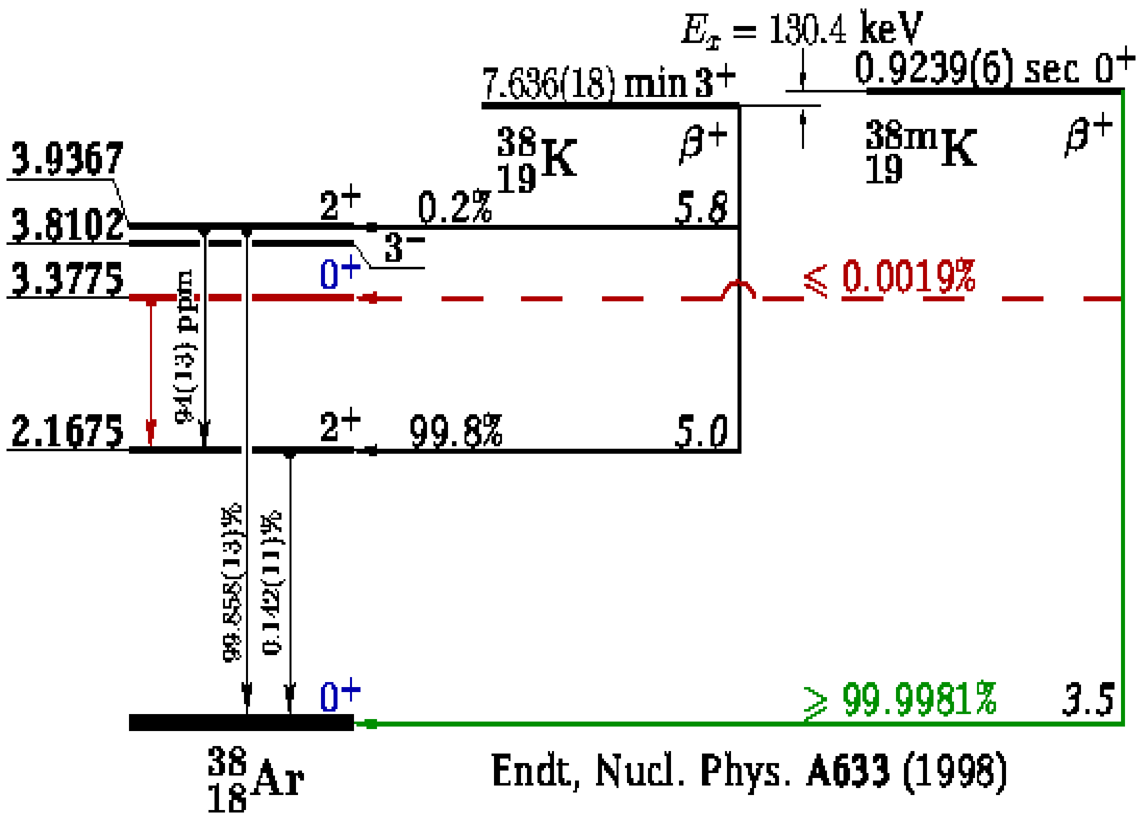
$$a_L^S = A_{LL} + A_{LR} \qquad a_R^S = A_{RR} + A_{RL}$$

SM: b = 0, $\mathbf{a}_{\beta\nu}$ = 1.0.

$C_S + C_S^{'} \sim$ **0.001 in MSSM, Profumo et al., PRD 75 075017**

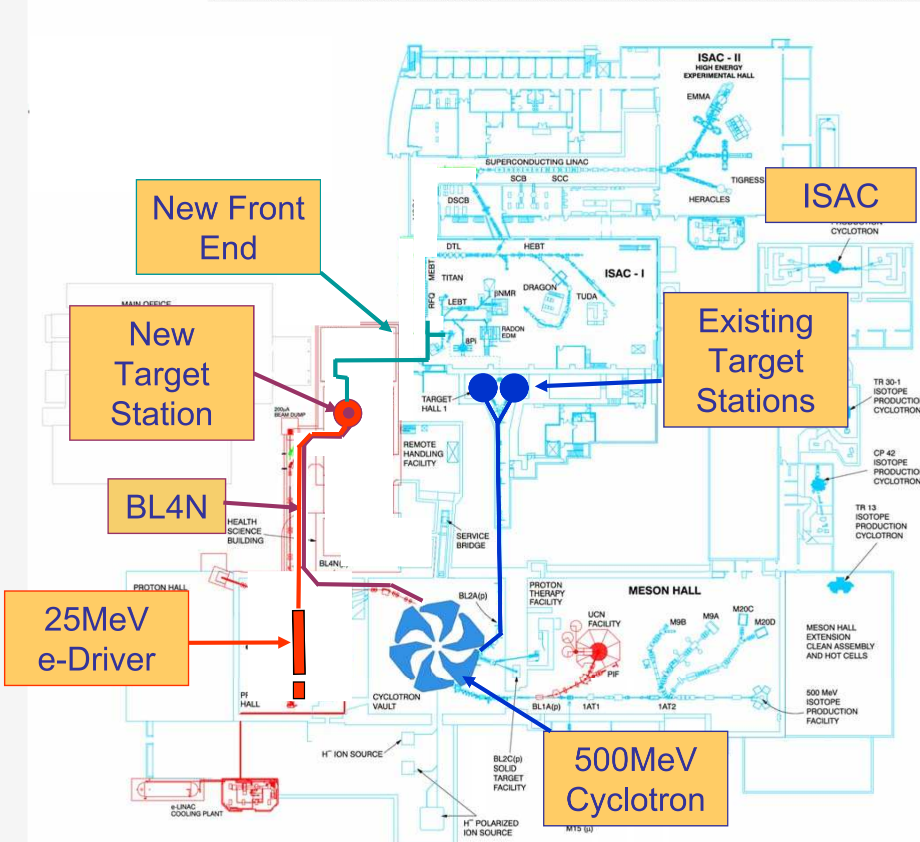
Measurement of $\beta - \nu$ Angular Correlation in ${}^{38m}K \xrightarrow{\beta^+} {}^{38}Ar$

$$Q({}^{38m}_{19}\mathrm{K}) = 5.02234(12)\ \mathrm{MeV}$$



Endt, Nucl. Phys. **A633** (1998)

Future (2010-2015)



Proposal:

By 2013:

- **Add a 25MeV electron driver to supply electrons to one new target**
- **Add a new ISAC front-end to deliver a second RIB beam to ISAC**

By 2015:

- **Add a new beam line from the cyclotron to deliver 500MeV protons to the new target**

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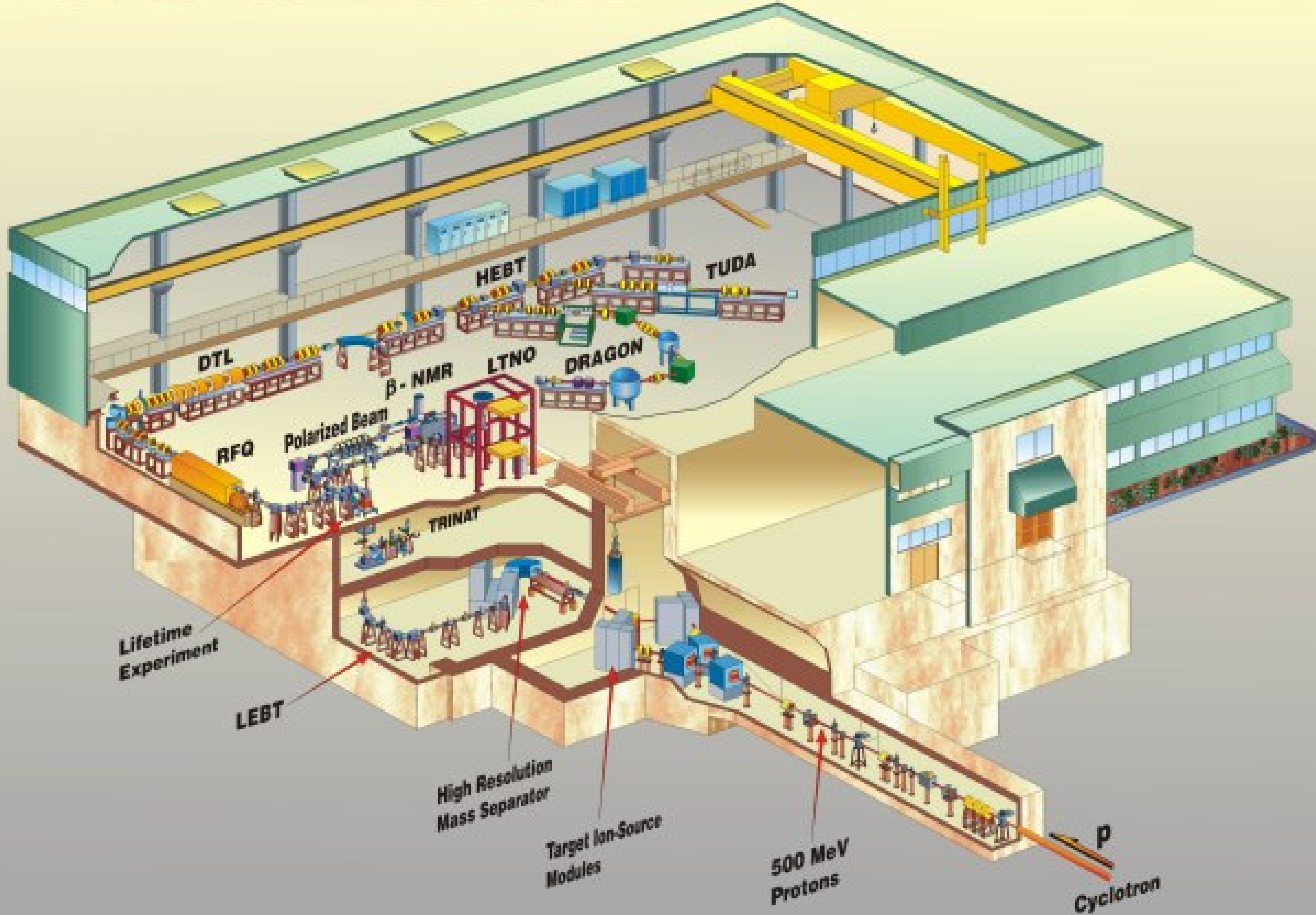
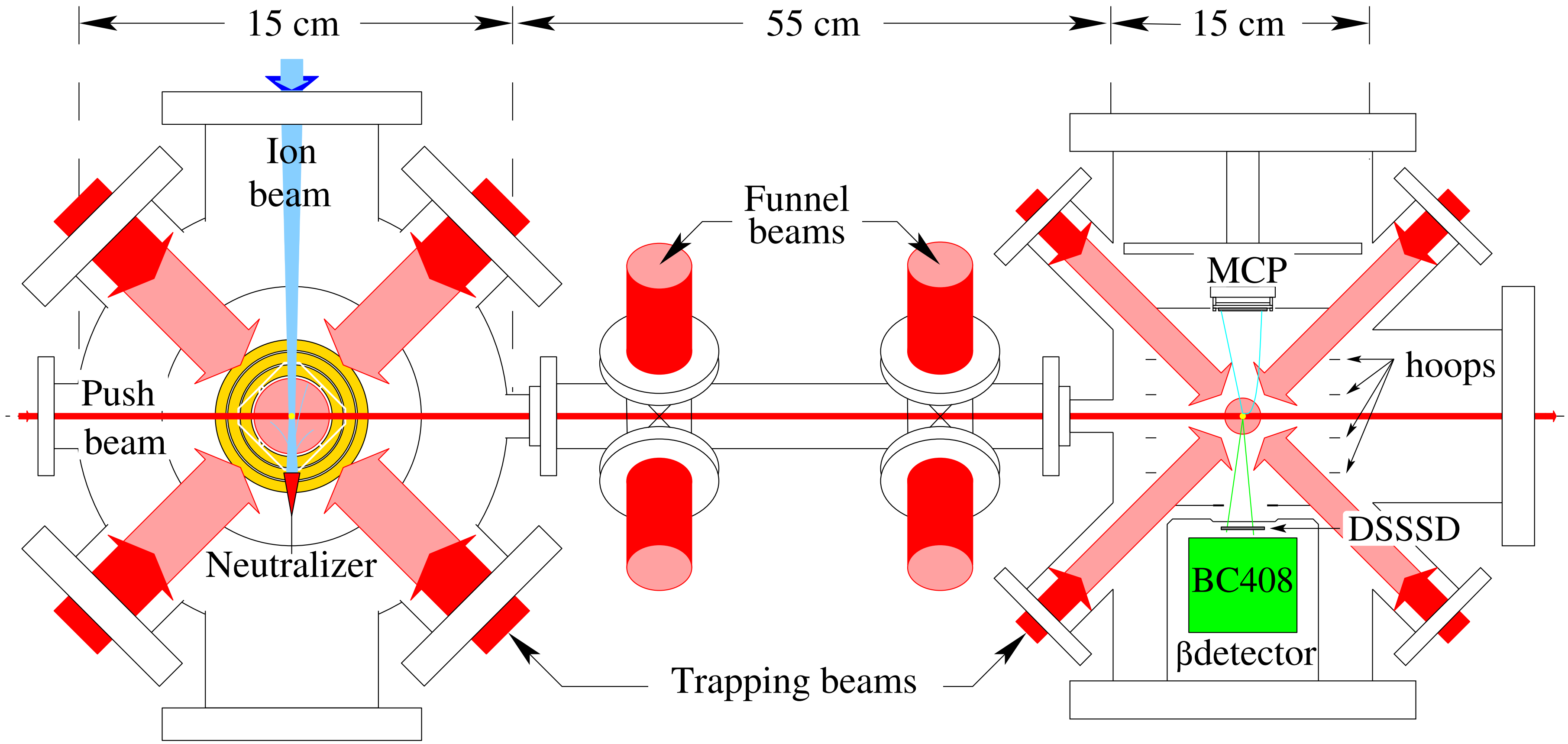
ISAC at TRIUMF



TRINAT DOUBLE MOT TRAPPING SYSTEM



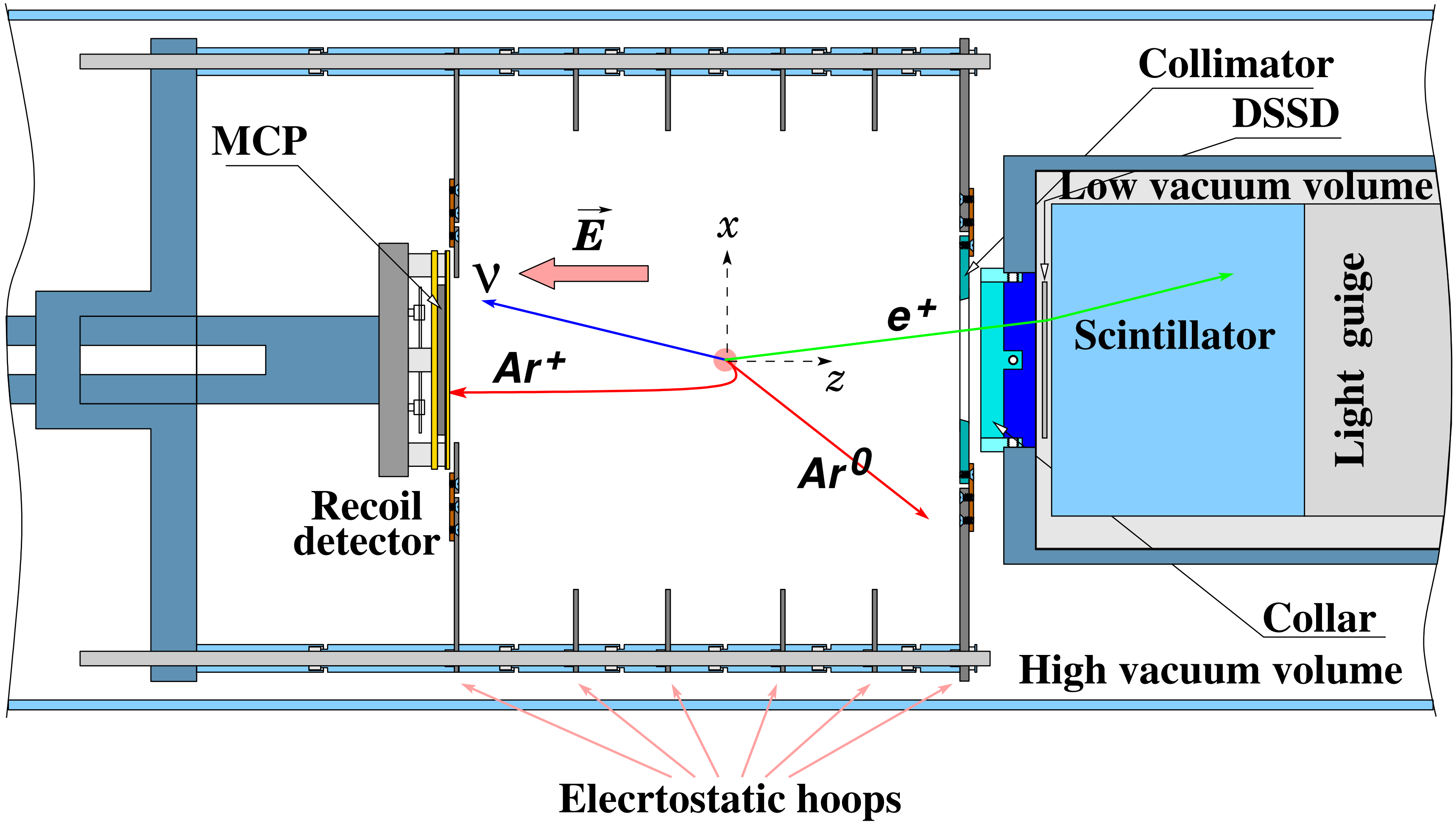
Collection chamber

- 95% $^{38gs}K^{+}$($t_{1/2}$= 7.64 min) + 5% $^{38m}K^{+}$($t_{1/2}$= 0.924 s)
- neutralization of $^{38}K^{+}$
- vapor cell trap
- 10^{-8} Torr
- 0.1% of ^{38m}K trapped
- 75% of trapped ^{38m}K moved

Detection chamber

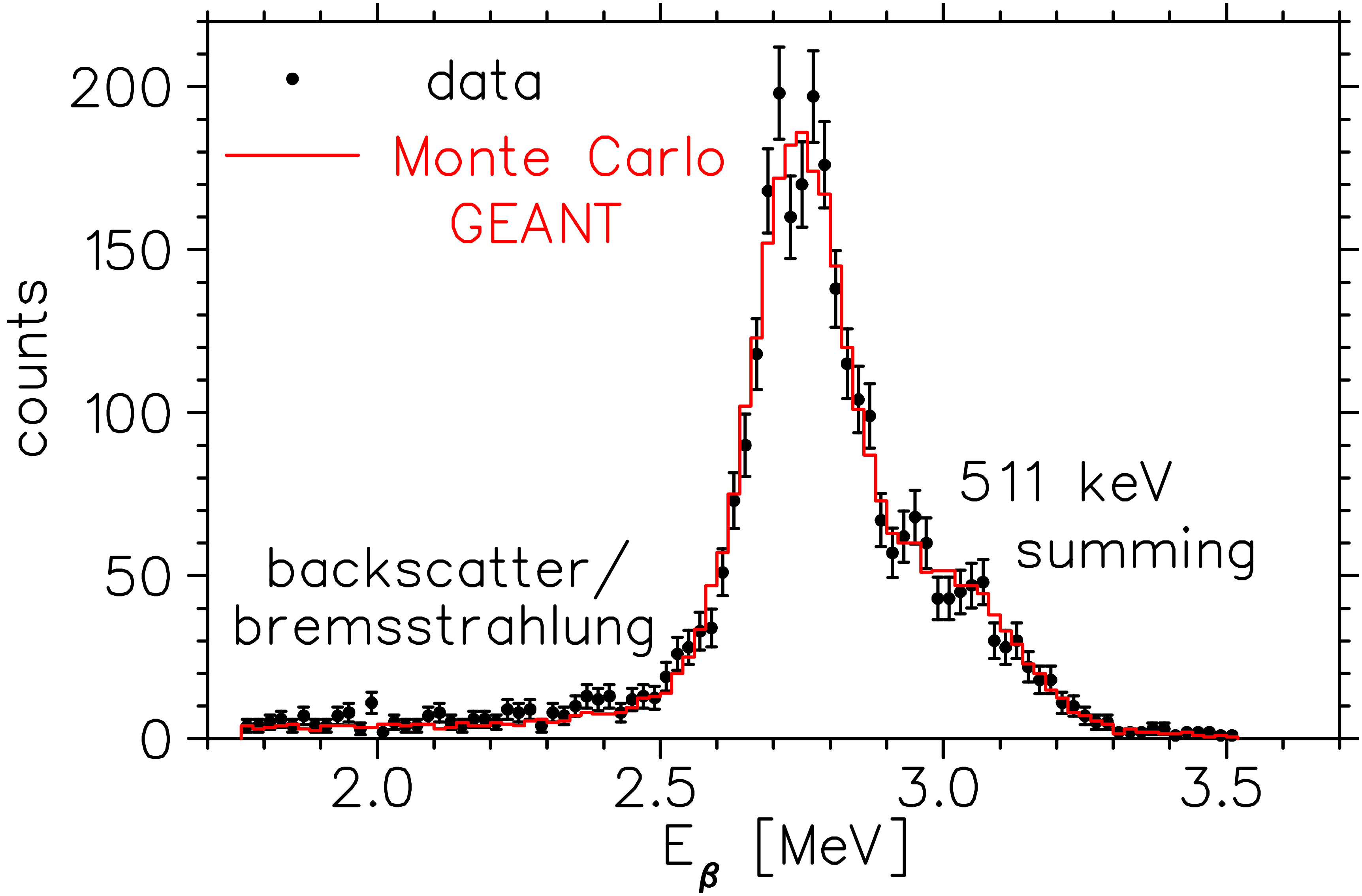
- 100% ^{38m}K, $t_{1/2}$= 0.924 s
- retrap from atomic beam
- $3{\cdot}10^{-10}$ Torr, $t^{trap}_{1/2}$= 30 s
- 0.75 mm FWHM trap size
- 2000 atoms in trap
- photoionization of ^{38m}K

TRINAT DETECTION SYSTEM FOR ^{38m}K DECAY



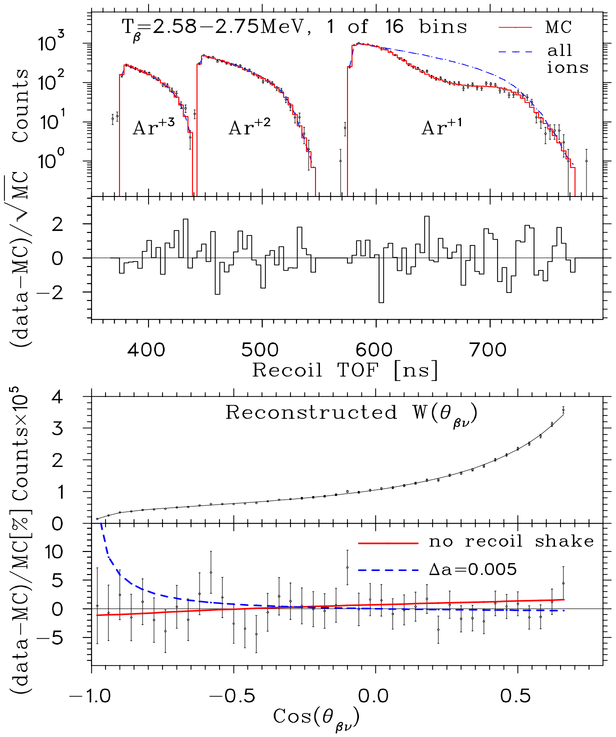
- High recoil collection and detection efficiencies due to $\boldsymbol{E}$-field
- Coincident detection of e^+ and recoils back-to-back
- Position information both from e^+ and recoil detectors
- Possibility to measure p_e and p_{recoil} and using them to determine p_ν.
- Chamber geometry suppresses recoiling ion detection from decays on walls and electrostatic hoops

Exploiting over-determined kinematics



Results: A. Gorelov *et al.*, PRL 94, 142501 (2005)

$$P(\theta) = 1 + b\frac{\mathrm{m}_\beta}{\mathrm{E}_\beta} + a_{\beta\nu}\frac{\mathrm{v}_\beta}{\mathrm{c}}cos(\theta)$$



For $|b| < $ **0.04,** $\langle E_\beta \rangle$**=3.3 MeV**

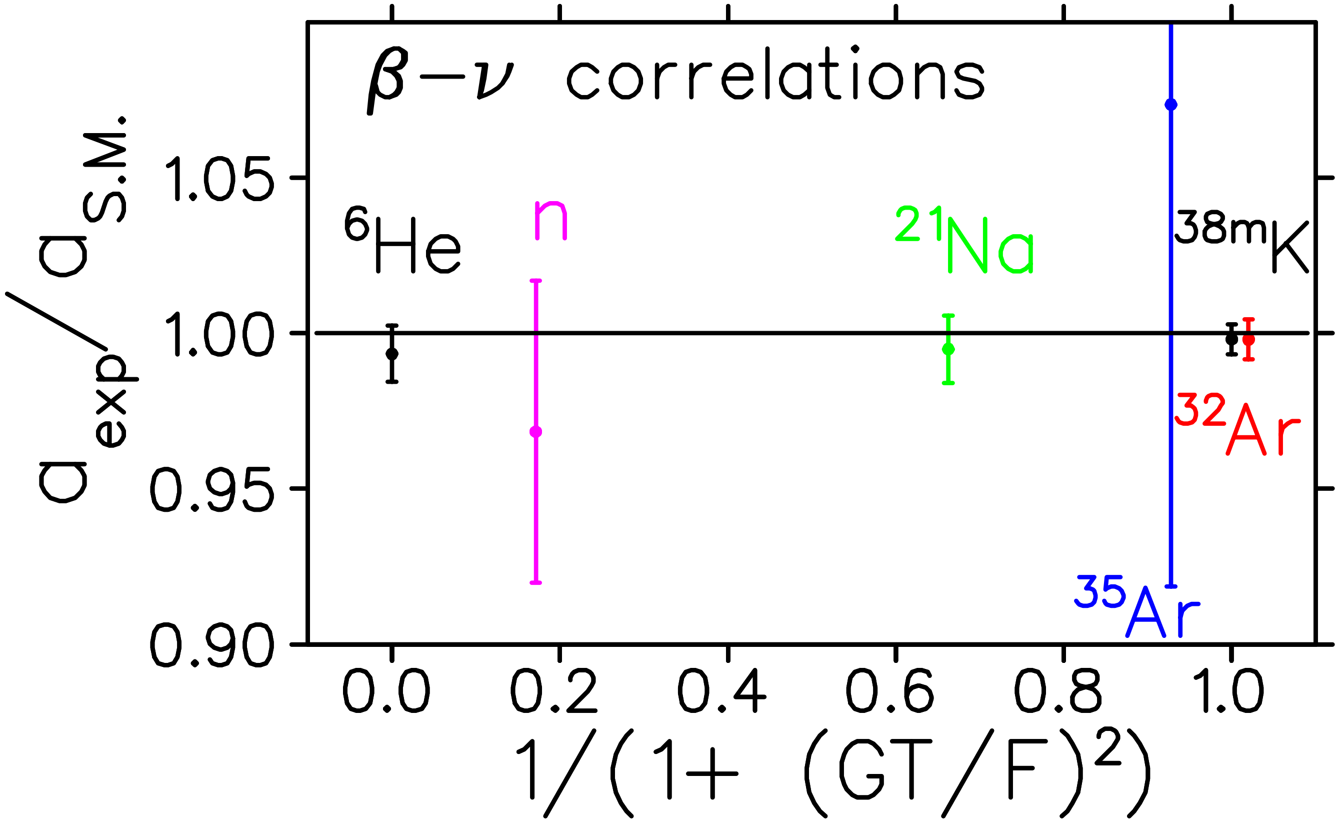
Define:

$$\tilde{a} = \frac{a_{\beta\nu}}{1+b\frac{m_\beta}{\langle E_\beta \rangle}}$$

$$\tilde{a} = 0.9981 \pm 0.0030^{+0.0032}_{-0.0037}$$

In agreement with the Standard Model.

Summary of results for a



^{32}Ar: E. G. Adelberger et al., Phys. Rev. Lett. 83, 1299(1999)

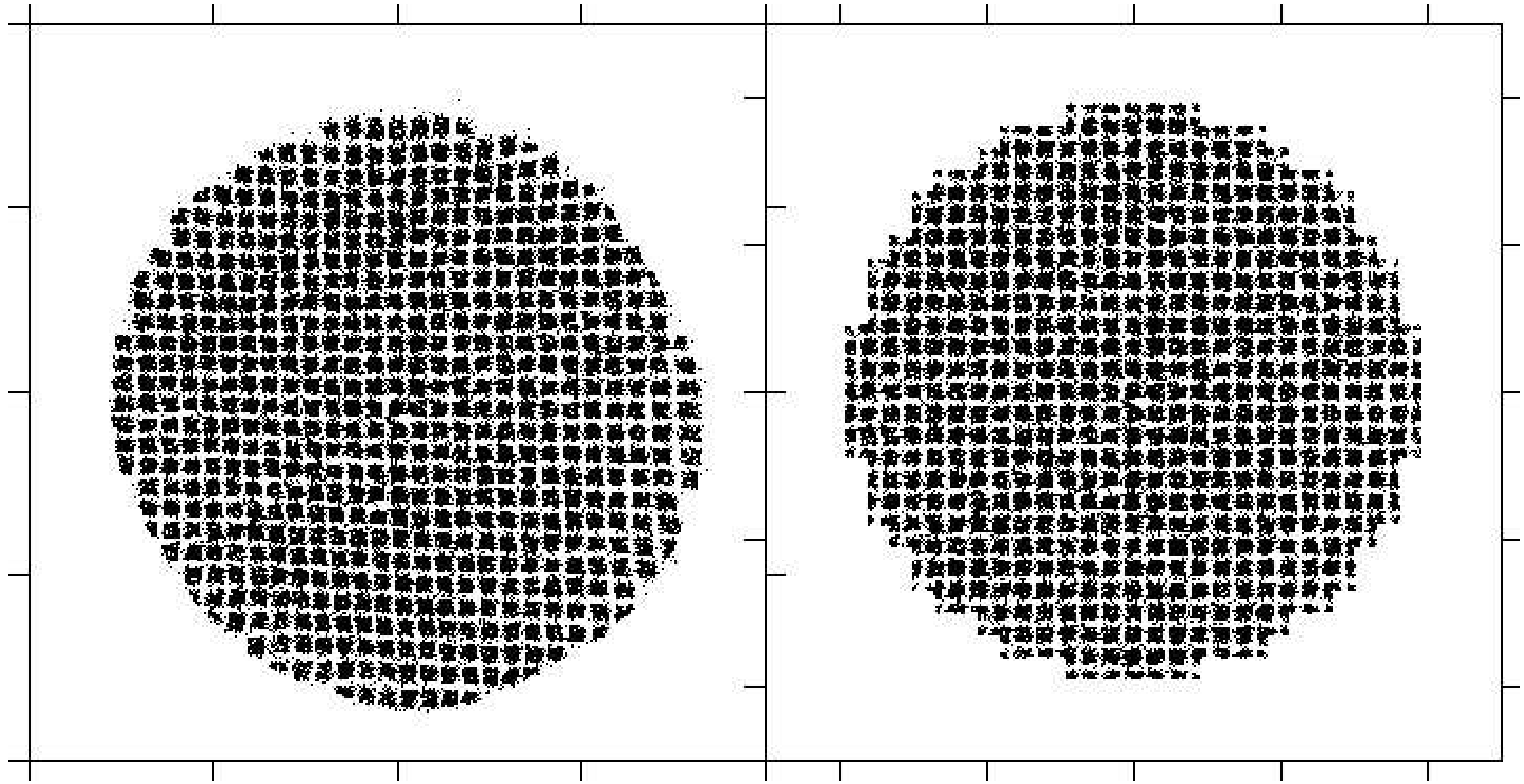
^{38m}K: A. Gorelov *et al.*, PRL 94, 142501 (2005)

^{21}Na: P.A. Vetter et al., Phys. Rev. C77, 035502 (2008)

Upgraded System for ^{38m}K decay measurement

- Reduce all systematic and statistical errors:
- New, larger MCP detector and β telescope - near 100% acceptance for ions. Improved low E_β detection for Fierz term measurement.
- Time and momentum focusing for better resolution and charge state separation.
- Higher beam intensity: 40μA vs. 1μA in previous experiment.
- New chamber design to accomodate all the above.

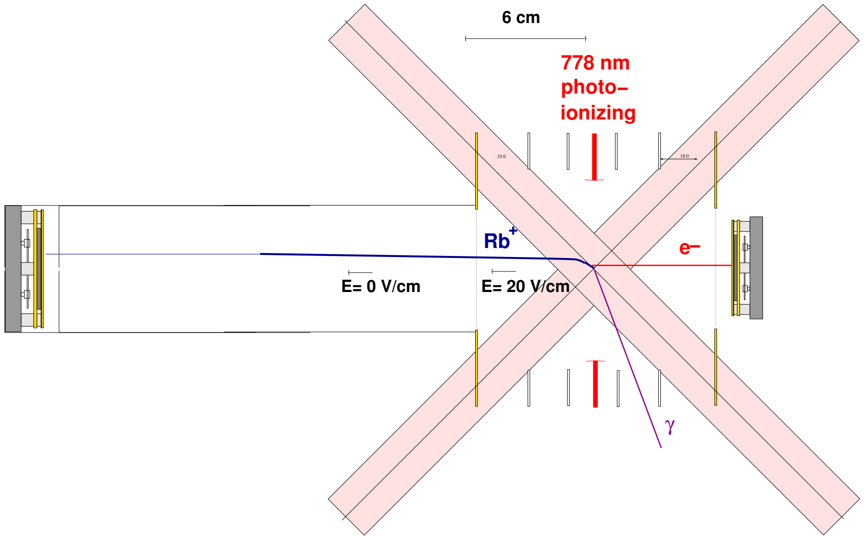
RECOIL DETECTOR SPATIAL CALIBRATION

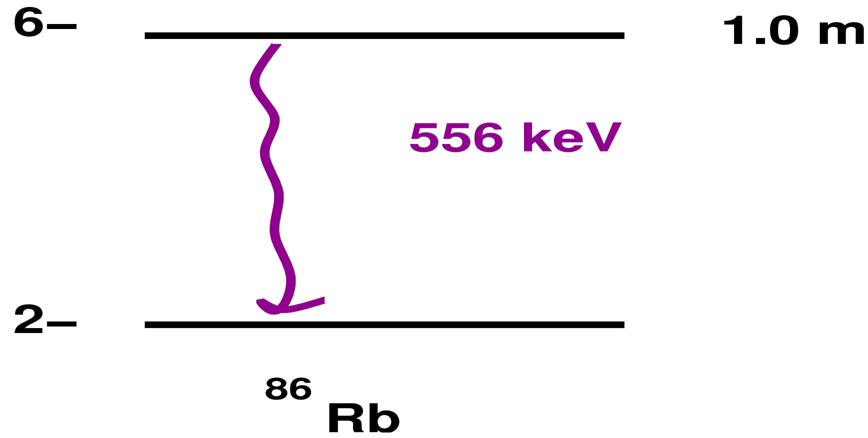


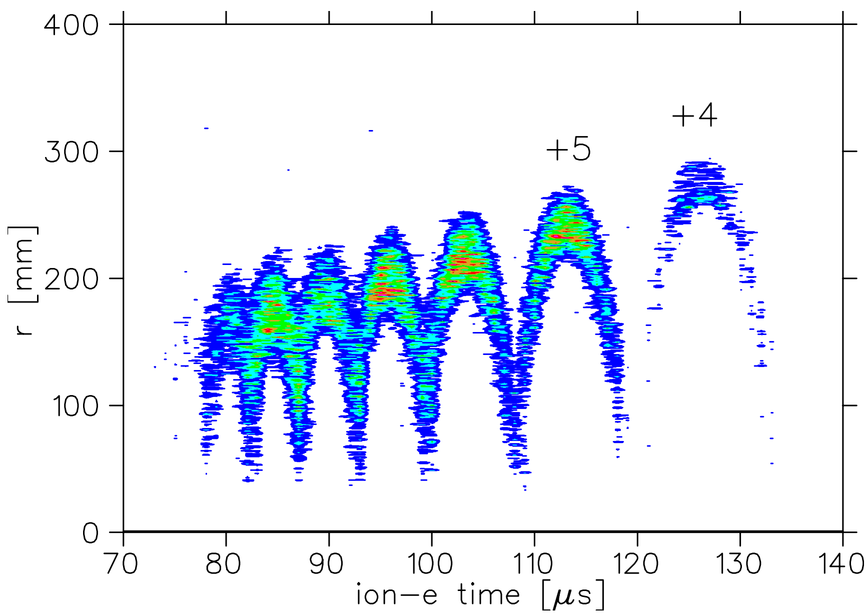
Calibration performed with precise mask (2mmx2mm hole, 1mm strip) and ^{148}Gd source. Evaluated resolution 0.25mm.

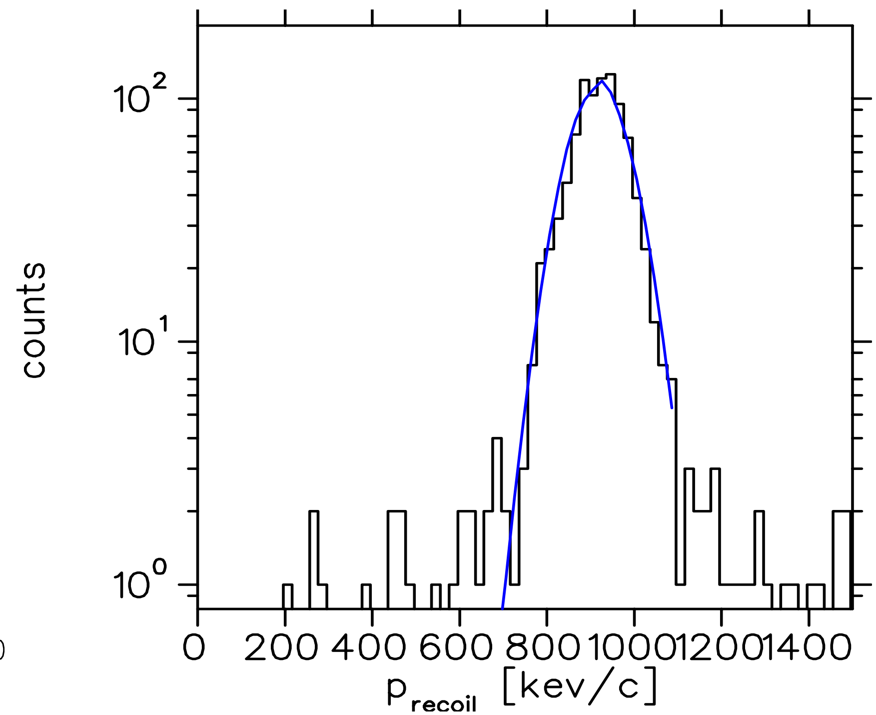
Time Focussing: p_{recoil} FROM 2% I.C. DECAY OF ^{86m}Rb

K,L e^- $\quad$ **$p =$ 920,932 kev/c** $\quad$ **$\Delta p/p \approx$ 0.03**



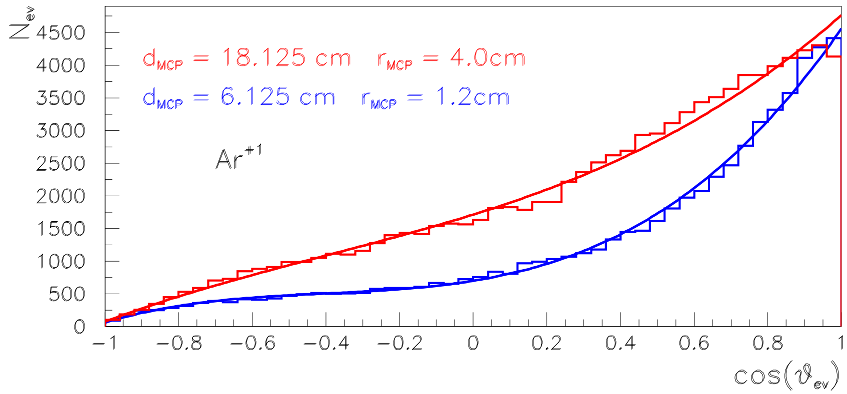


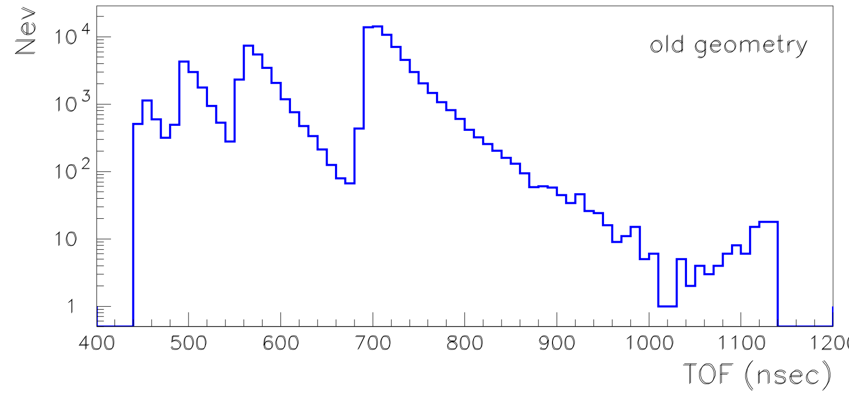


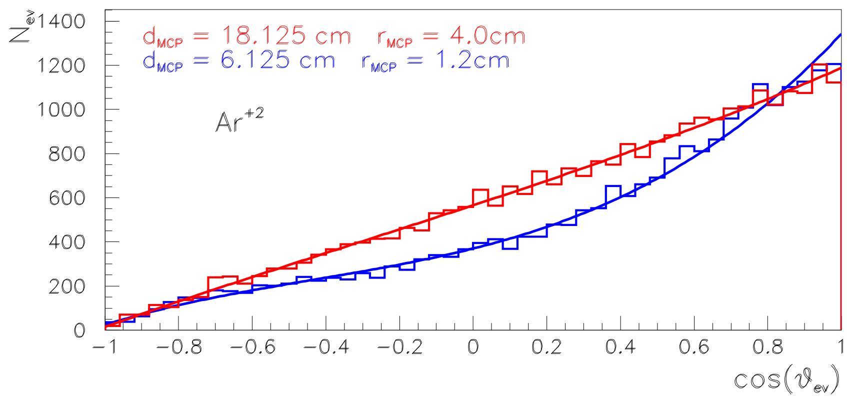


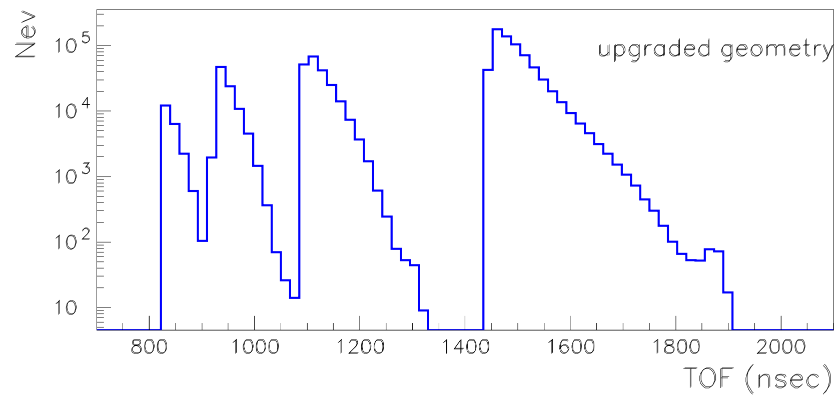
Improved acceptance and time/charge-state resolution

Simulations for ^{38m}K decay







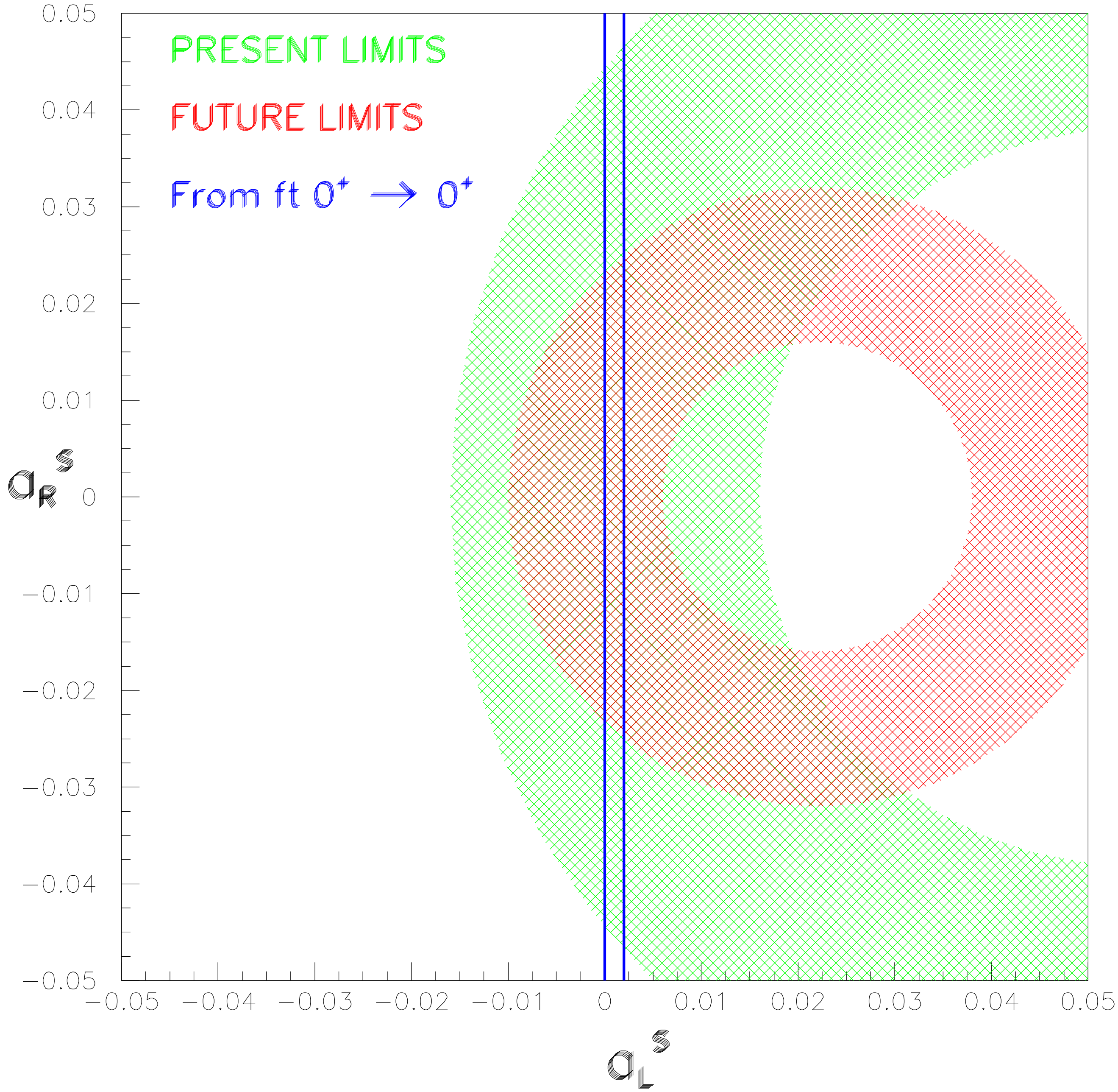


PRESENT AND PLANNED ERRORS (^{38m}K decay)

	PRESENT	FUTURE
Applied electric field		
E-field non-uniformity	0.0010	0.0003
E-field/trap size	0.0012	0.0004
Beta-detector response		
Energy calibration	0.0016	0.0008
Line shape tail/total	0.0013	0.0003
511keV Compton summing	0.0002	0.0004
Recoil Detector efficiency		
MCP incident recoil angle	0.0006	0.0004
MCP incident ion energy	0.0010	0.0003
Prompt peak	0.0009	
Transverse trap position	$^{+0.0000}_{-0.0004}$	
Electron shake-off	$^{+0.0000}_{-0.0015}$	0.0003
Total systematic error	$^{+0.0030}_{-0.0034}$	0.0012

- **Most errors determined by statistics-limited data evaluation.**
- Further improvements: use all kinematic information.
- Extend analysis to lower E_β to measure b.

Limits on Scalar Interaction



Polarization Observables

$$dW =$$
$$dW_o(1 + \frac{\vec{p_\beta} \cdot \vec{p_\nu}}{E_\beta E_\nu} a_{\beta\nu} + \frac{\Gamma m_e}{E_\beta} b + \frac{\vec{J}}{J} \cdot [\frac{\vec{p_\beta}}{E_\beta} A_\beta + \frac{\vec{p_\nu}}{E_\nu} B_\nu + \frac{\vec{p_\beta} \times \vec{p_\nu}}{E_\beta E_\nu} D]$$
$$+c[\frac{\vec{p_\beta} \cdot \vec{p_\nu}}{3E_\beta E_\nu} - \frac{(\vec{p_\beta} \cdot \vec{j})(\vec{p_\nu} \cdot \vec{j})}{E_\beta E_\nu}][\frac{J(J+1) - 3 < (\vec{J} \cdot \vec{j})^2 >}{J(2J-1)}])$$

Asymmetry $= \frac{\sigma(\uparrow) - \sigma(\downarrow)}{\sigma(\uparrow) + \sigma(\downarrow)}$

$\vec{J} \parallel \vec{P_\beta} \Longrightarrow$ **measure** A_β **(**β **singles or coin. with recoil)**

$\vec{J} \perp \vec{P_\beta}, \quad \vec{P_\nu} = \vec{P_R} - \vec{P_\beta} \quad \Longrightarrow dW \propto \frac{\vec{J}}{J} \cdot \left[B_\nu \vec{P_R} + D \frac{(\vec{P_\beta} \times \vec{P_R})}{E_\beta} \right]$

Measure B_ν **from Recoil Asymmetry in** $\vec{P_R} \parallel \vec{J}$ **plane**

Measure D **from Recoil Asymmetry in** $\vec{P_R} \perp \vec{J}$ **plane**

Right-handed Currents

$$|W_L>= cos\zeta|W_1> -sin\zeta|W_2>$$

$$|W_R>= sin\zeta|W_1> +cos\zeta|W_2>$$

Define: $x = (M_L/M_R)^2 - \zeta$ **and** $y = (M_L/M_R)^2 + \zeta$

$\lambda \equiv g_A M_{GT}/g_V M_F$

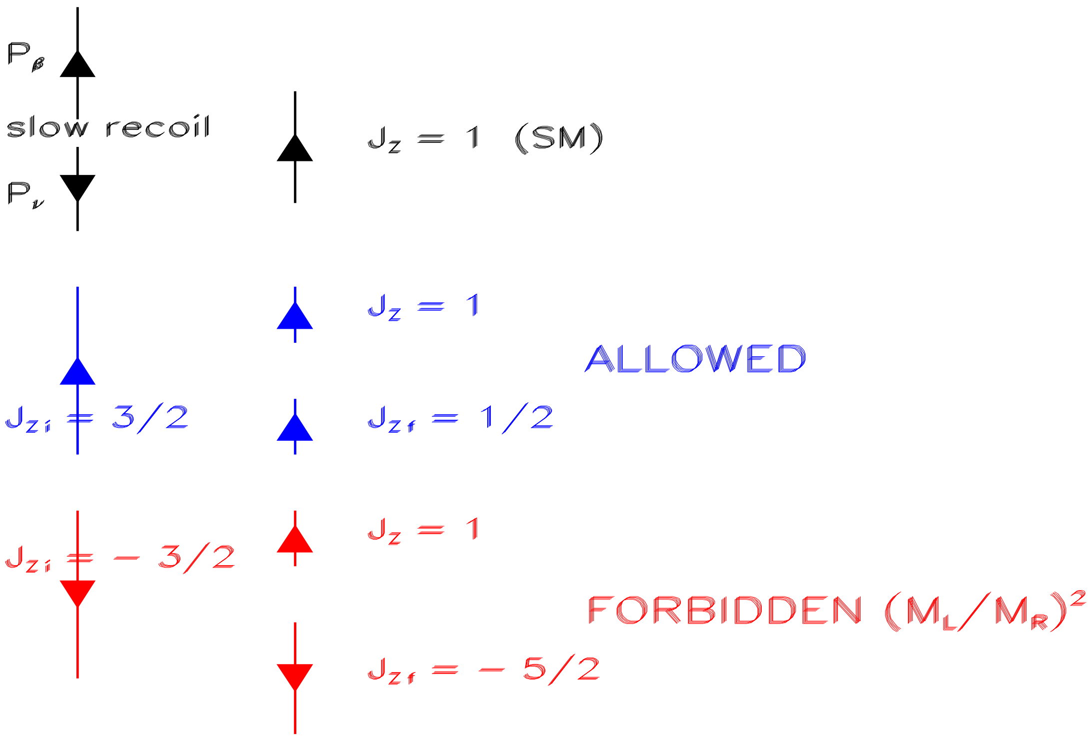
$$A_\beta = \frac{-2\lambda}{1+\lambda^2}\left[\frac{\lambda(1-y^2)}{5(1+y^2)} - (1-xy)\sqrt{\frac{3(1+x^2)}{5(1+y^2)}}\,\right]$$

$$B_\nu = \frac{-2\lambda}{1+\lambda^2}\left[\frac{\lambda(1-y^2)}{5(1+y^2)} + (1-xy)\sqrt{\frac{3(1+x^2)}{5(1+y^2)}}\,\right]$$

$$R_{slow} \equiv \frac{dW(\vec{J}\cdot\vec{p}_\beta = -1)}{dW(\vec{J}\cdot\vec{p}_\beta = +1)} = \frac{1-a-2c/3-(A+B)}{1-a-2c/3+(A+B)} = y^2$$

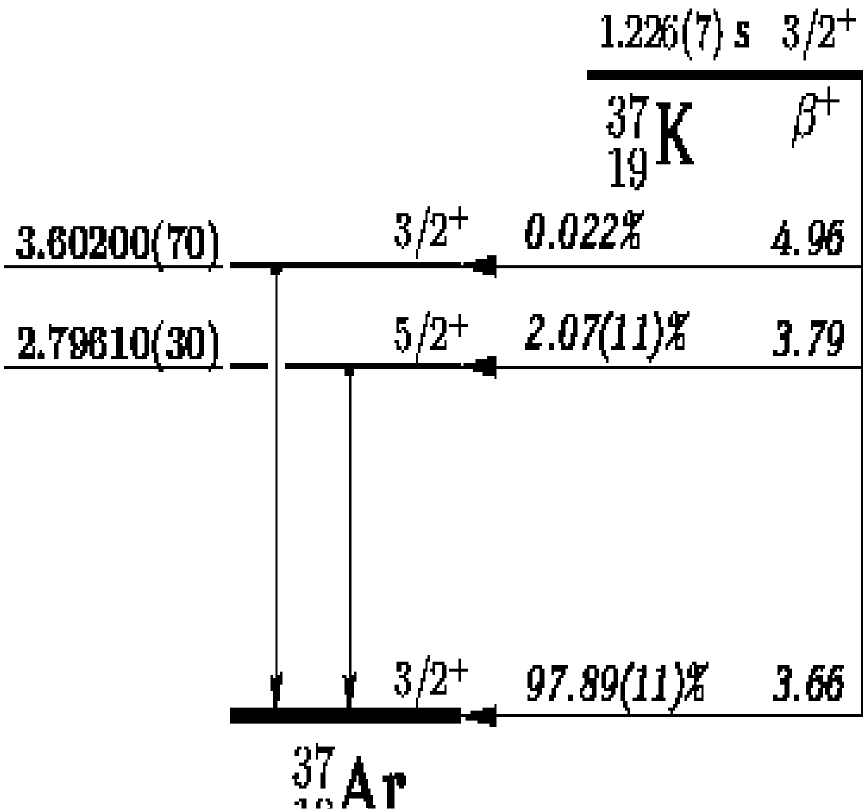
The R_{slow} Concept

$$^{37}K \rightarrow {}^{37}Ar\ \beta\ \nu \qquad 3/2^+ \rightarrow 3/2^+$$



Measurement of $\beta - \nu$ Angular Correlation in Polarized $^{37}K \xrightarrow{\beta^+} {}^{37}Ar$

More precise determination of decay branching ratios underway in Texas A & M University



$Q(^{37}\mathrm{K}) = 5.1265(15)$ MeV

$M_{GT}/M_F = -0.5754(16)$

Hagberg et al., Phys. Rev. C 56 (1997)

Coefficients of $\beta - \nu$ Angular Correlation in Polarized $^{37}K \xrightarrow{\beta^+} {}^{37}Ar$

Calculated with the Standard Model assuming

$\lambda \equiv g_A M_{GT}/g_V M_F = -0.5754 \pm 0.0018$

Maximal Parity Violation

observable	$a_{\beta\nu}$	A_β	B_ν	c
value	0.6683	–0.5702	–0.7692	0.1990
error[1]	0.0013	0.0005	0.0013	0.0008

[1] **Due to error in λ**

$$b = D = R_{slow} = 0$$

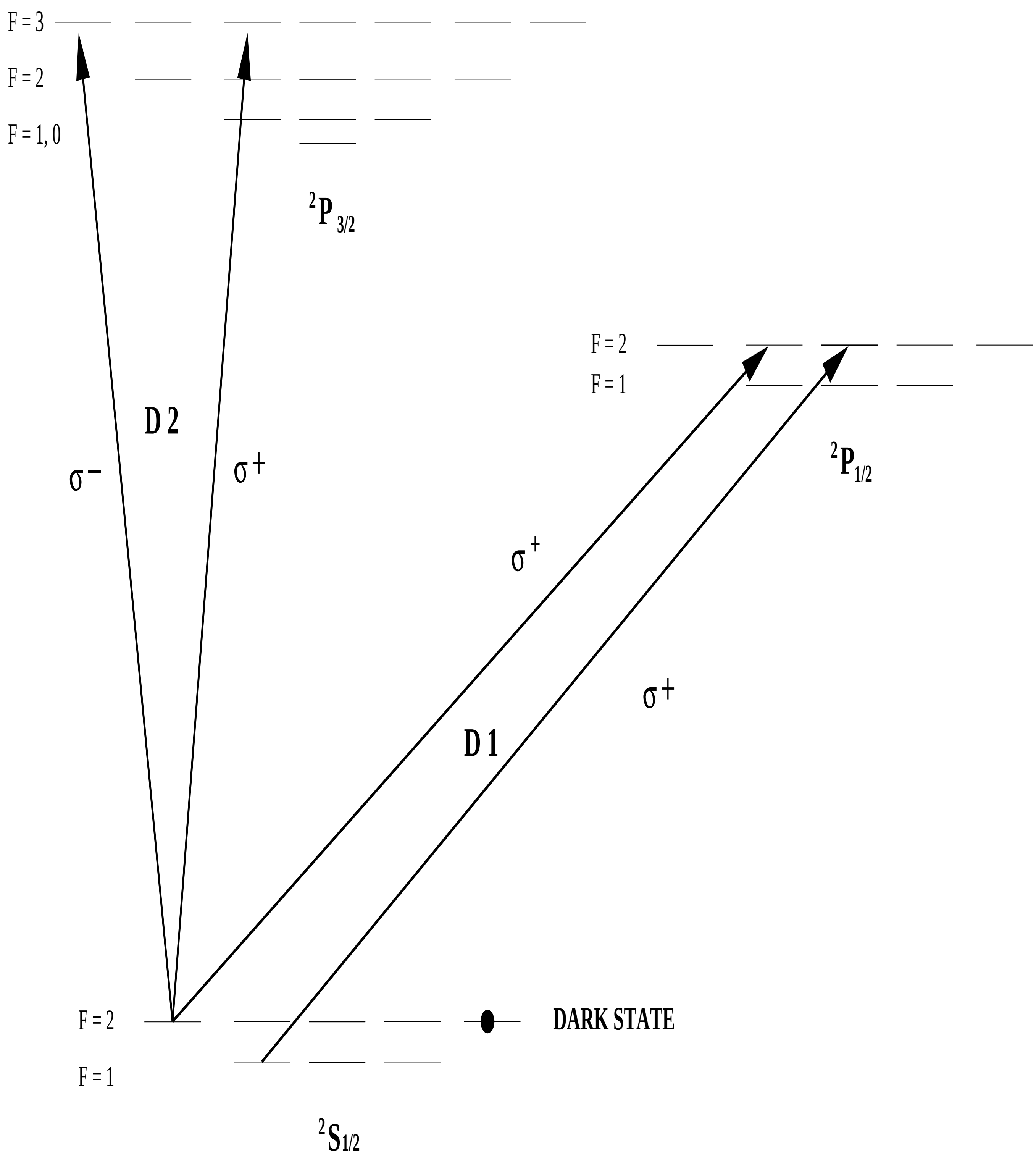
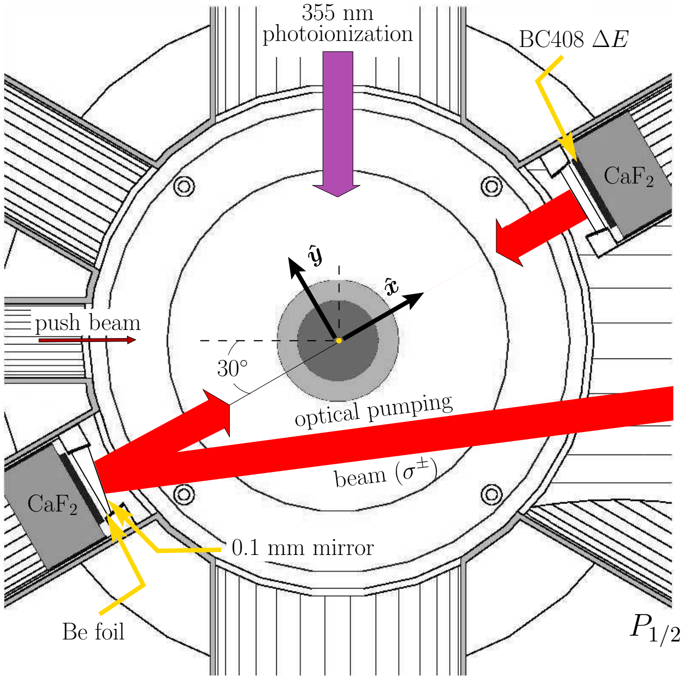


Figure 1: *Hyperfine level scheme of the $^2S_{1/2}$ ground*

Optical Pumping



$\hat{x}$ = polarization axis
= phoswich detector axis
$\hat{z}$ = MCP – β–telescope axis

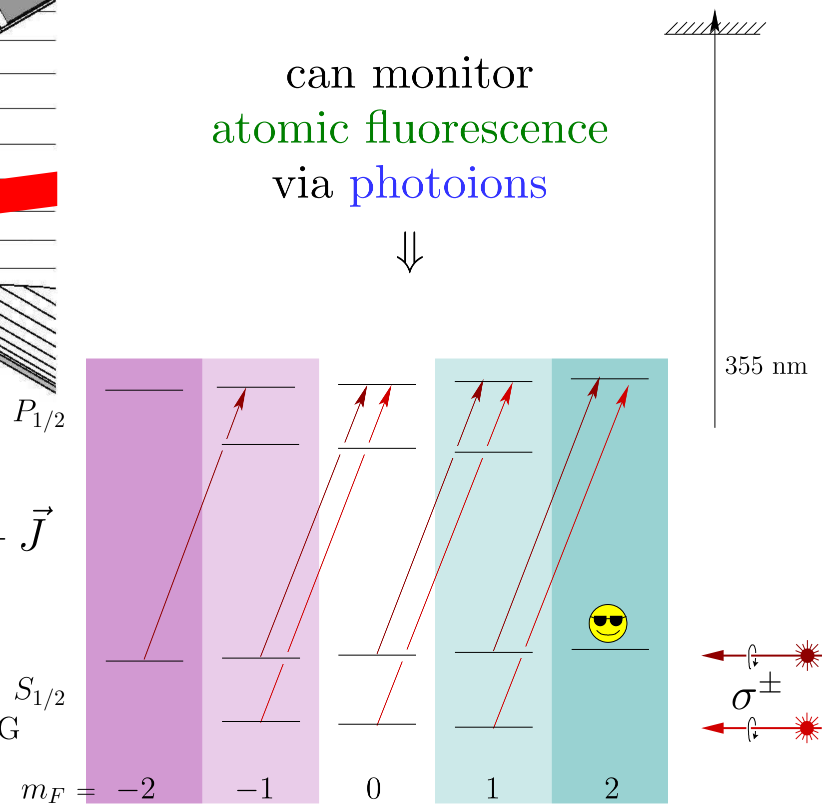
can monitor
atomic fluorescence
via photoions
⇓

$$\vec{F} = \vec{I} + \vec{J}$$

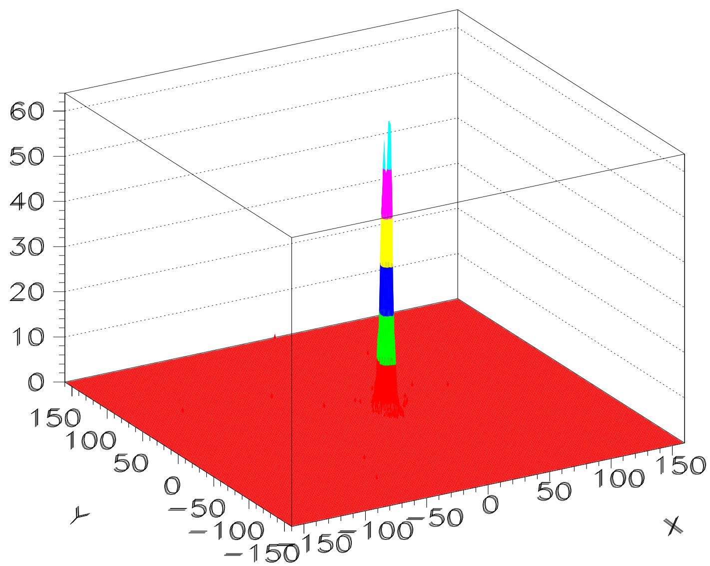
$I = \frac{3}{2}$

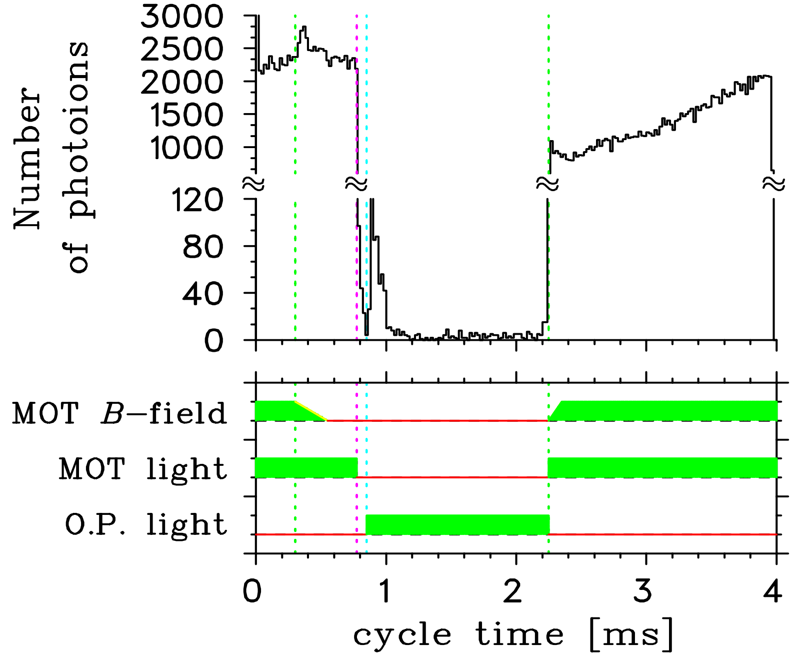
$J = \frac{1}{2}$

$\vec{B}_{\mathrm{OP}} = 2.5$ G



Determination of the Polarization

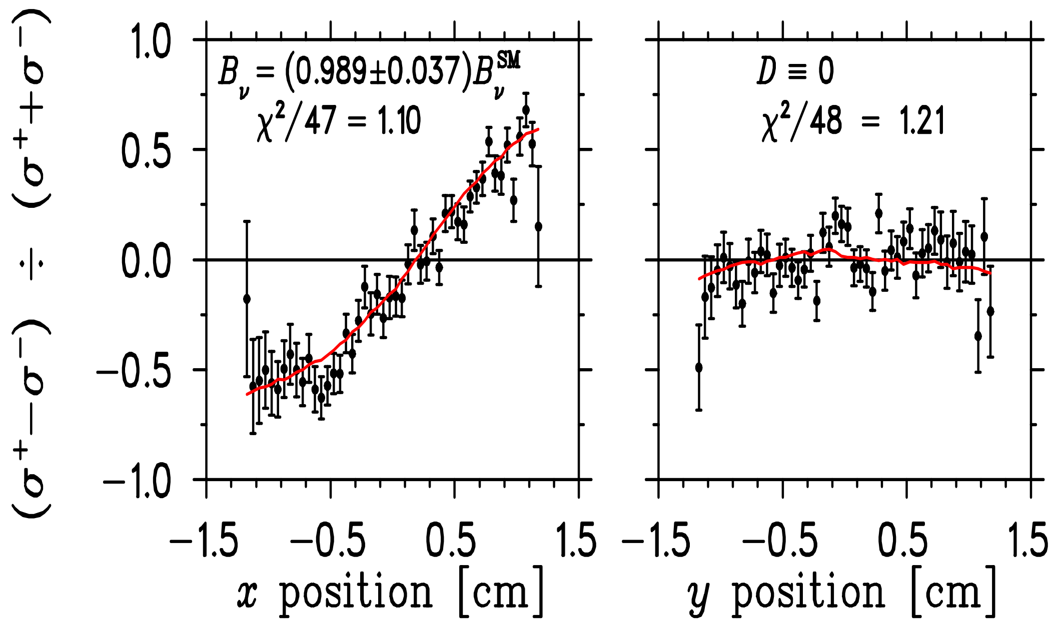




Photoions detected in MCP

Trap Cycle

Measure B_ν from Recoil Asymmetry in $\hat{x} - \hat{z}$ plane
Measure D from Recoil Asymmetry in $\hat{y} - \hat{z}$ plane



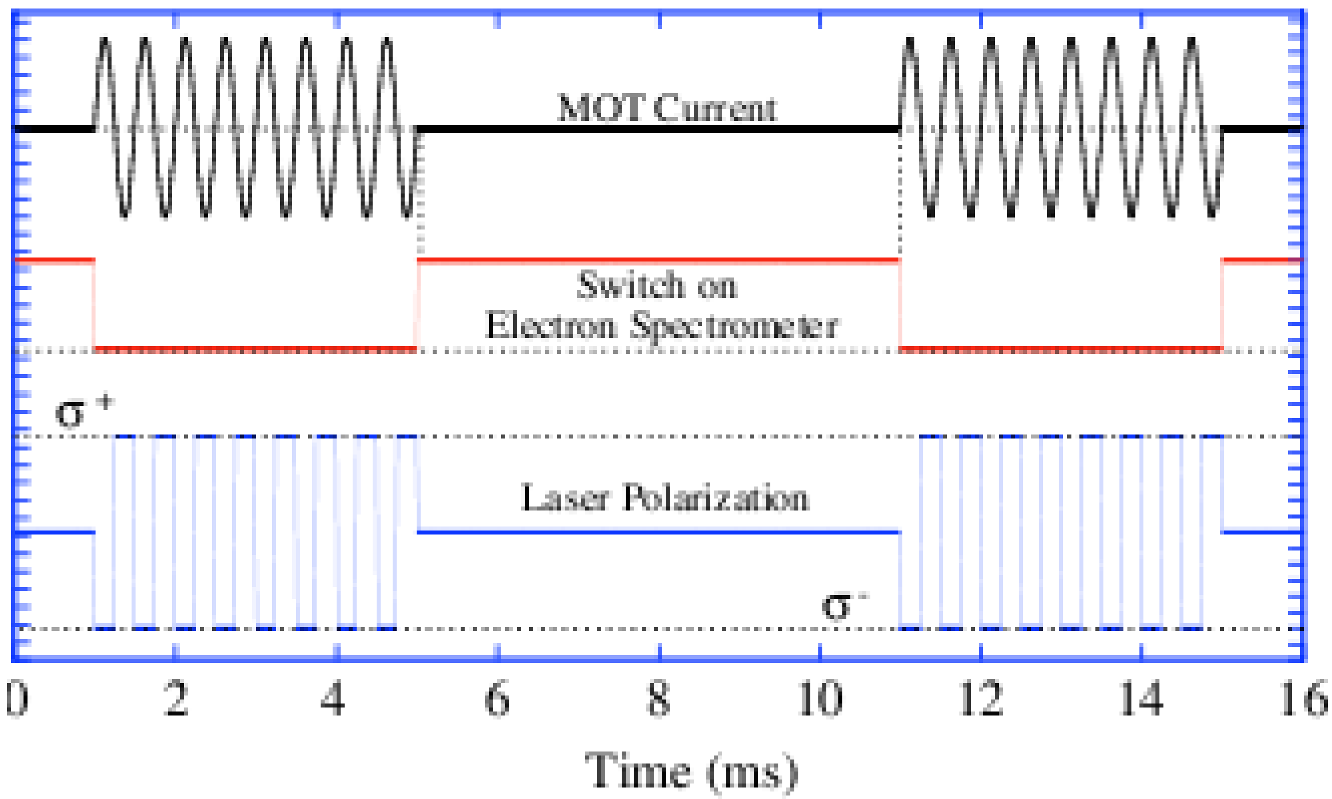
$$B_\nu \quad = \quad 0.755 \pm 0.020(stat) \pm 0.013(syst)$$

D. Melconian *et al.* PL B 649, 370 (2007)

Upgraded Experimental System

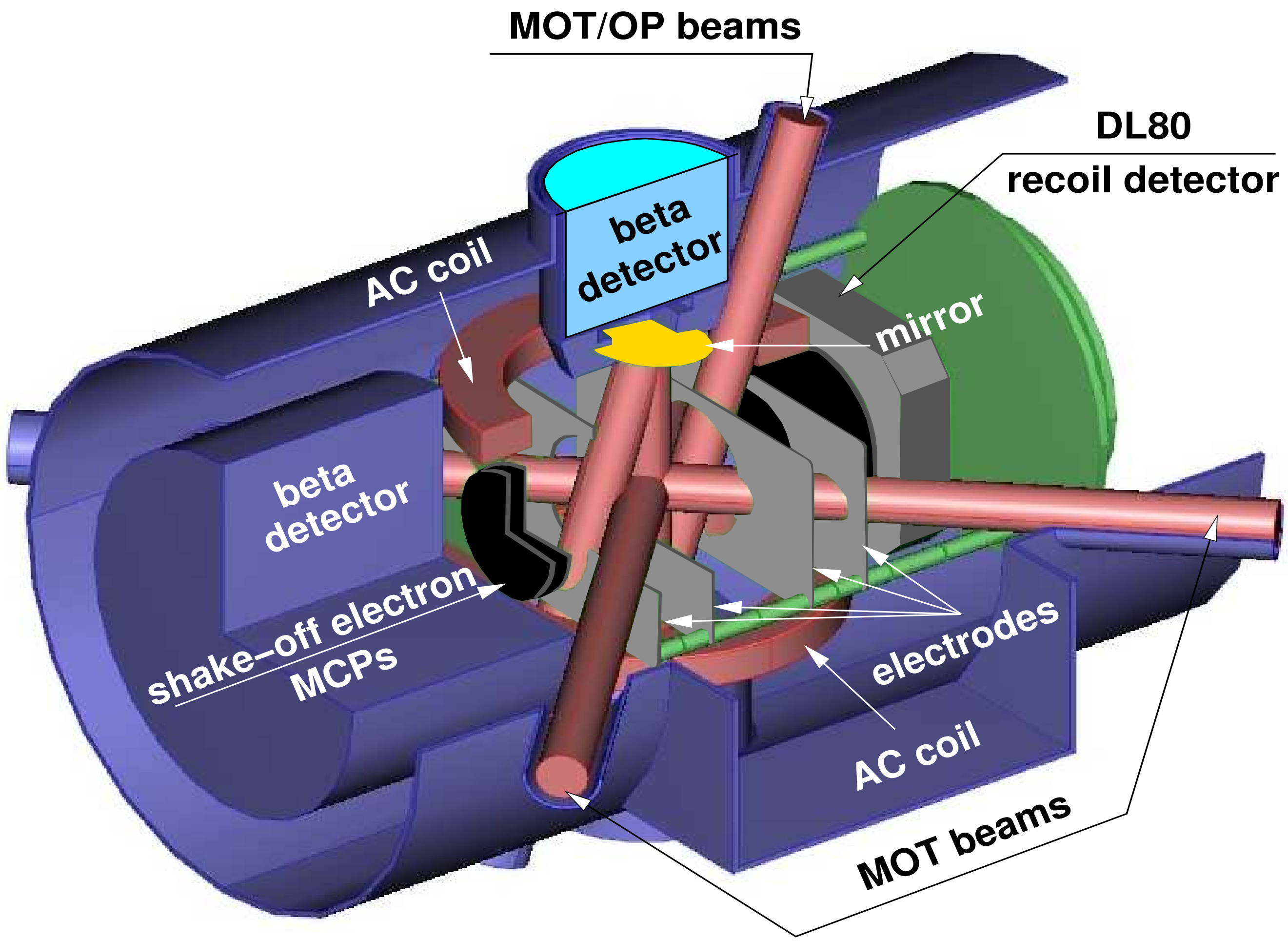
- **Reduce all systematic and statistical errors:**
- **New, larger MCP detector and β telescope - near 100% acceptance for ions. Improved low E_β detection for Fierz term measurement.**
- **New polarization detectors with Si MSD and plastic scintillator. Position information and better resolution.**
- **Time and momentum focusing for better resolution and charge state separation.**
- **Shakeoff electron detection for background suppression.**
- **Better trapping/polarization cycle by using AC MOT.**
- **Higher beam intensity: 40μA vs. 1μA in previous experiment.**
- **New chamber design to accomodate all the above.**

The principle of AC MOT

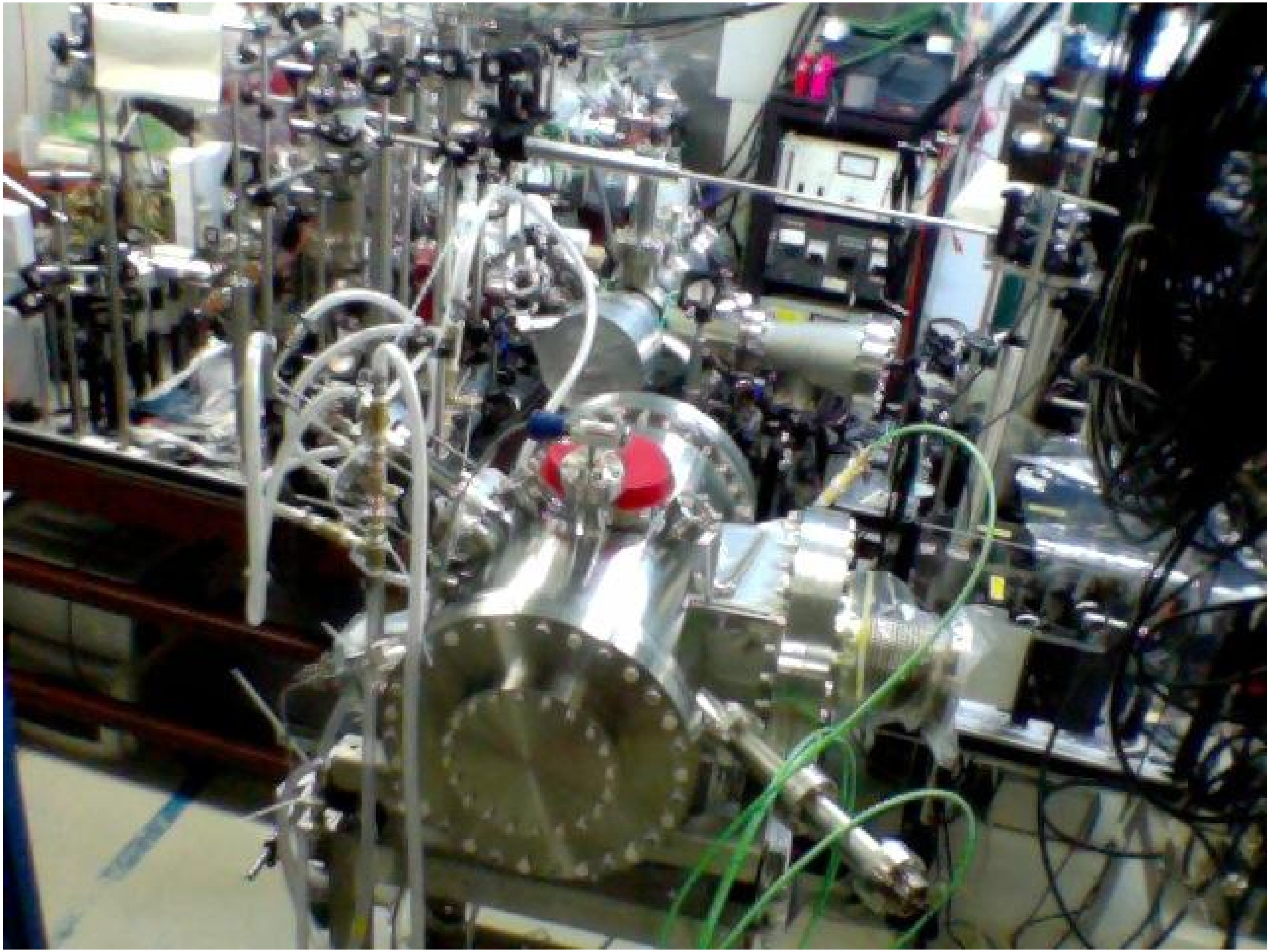


M. Harvey and A.J. Murray Phys. Rev. Lett. 101, 173201 (2008)

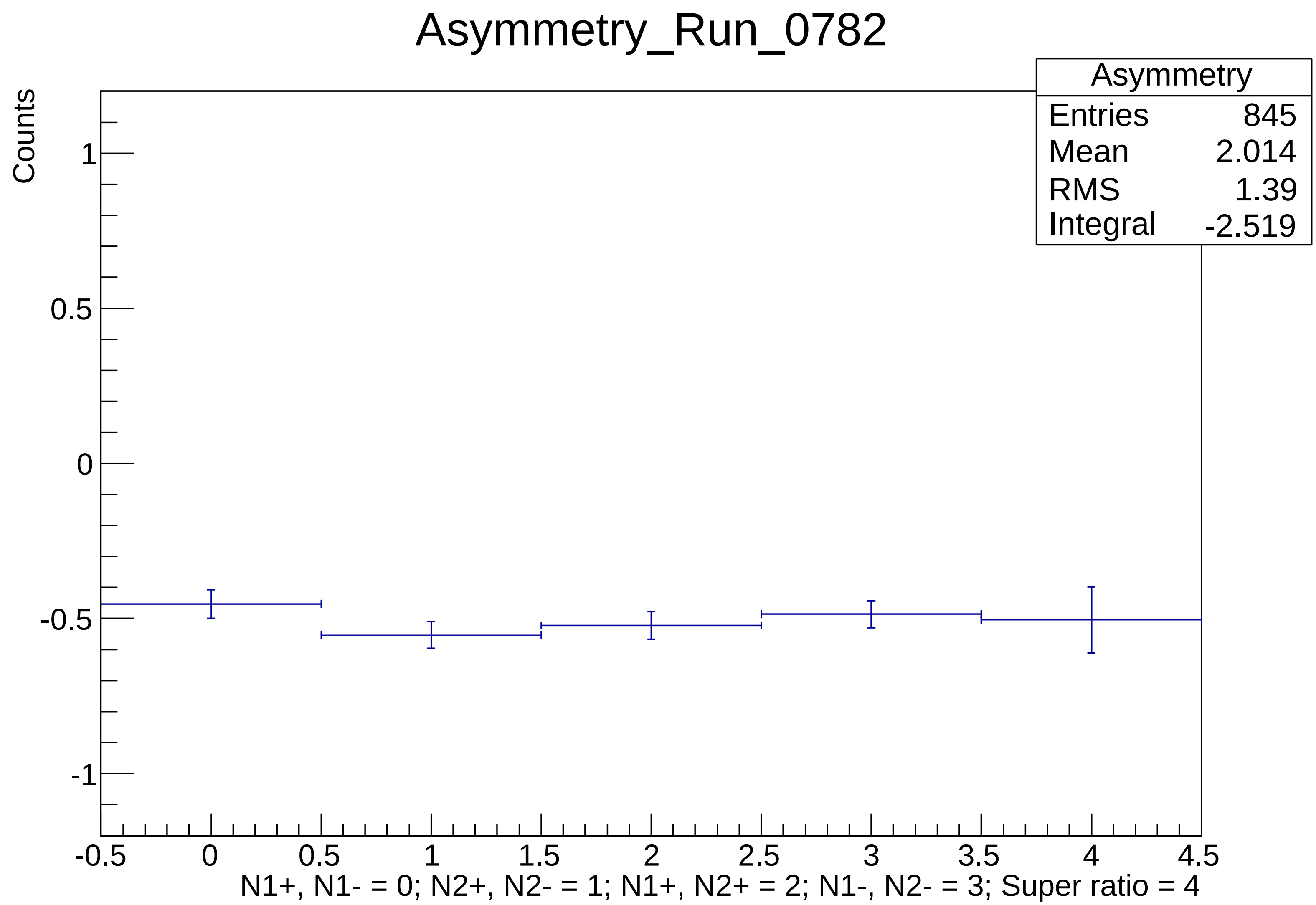
NEW DETECTION CHAMBER FOR ^{37}K



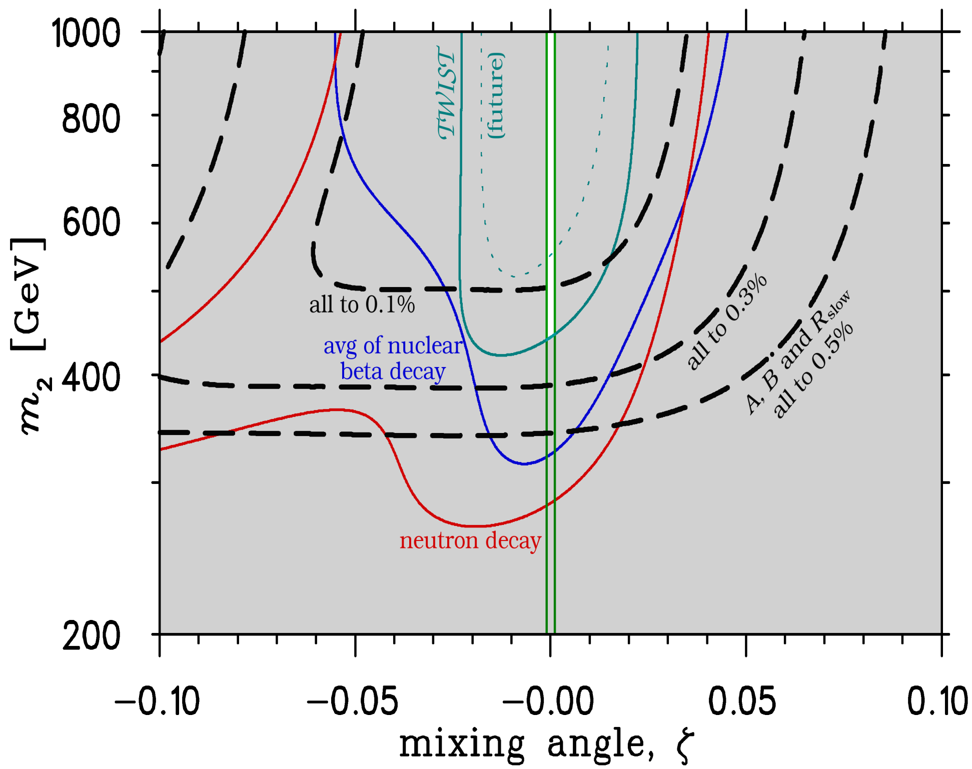
- Position sensitivity on all beta and recoil detectors
- Larger beta and recoil detectors will improve statistics
- AC MOT will speed up switching from MOT cycle to OP cycle
- Improvement of a weak magnetic field during OP will improve polarization
- Coincidences with shake off electron MCP will reduce background for competitive measurements of beta asymmetry



JUST MEASURED



Limits on Right-Handed Currents



Tensor Interaction

The angular distribution of recoiling daughter nuclei of polarized β emitters, S.B. Treiman PR 110, 448 (1957):

$$W(\theta_r)d(\cos\theta_r) = \{1 + \frac{1}{3}c'\chi_2 - \mathrm{P}(A_\beta + B_\nu)\chi_1 \cos\theta_r - c'\chi_2 \cos^2\theta_r\}d(\cos\theta_r)$$

$\chi_1,\ \chi_2$ **kinematical functions,** $\quad c' = c\frac{J(J+1)-3\langle(\vec{J}\cdot\vec{j})^2\rangle}{J(2J-1)}$.

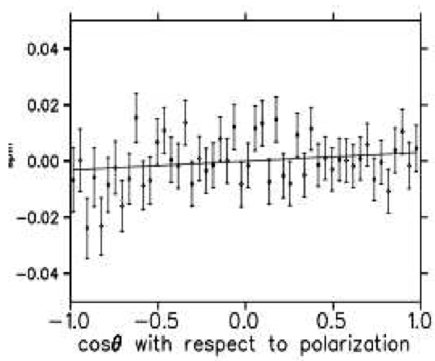
For pure GT transitions and no Tensor Interaction: $A_\beta + B_\nu = 0$

$5/8(A_\beta + B_\nu) = 2C_T C'_T + \frac{m_\beta}{E_\beta}(C_T - C'_T)$

And can be deduced from Asymmetry measurements:

$$A_{\rm spin} = \frac{W[\theta,P] - W[\theta,-P]}{W[\theta,P] + W[\theta,-P]} = \frac{\chi_1 P(A_\beta + B_\nu)\cos\theta}{1 + c'\chi_2 + c'\chi_2\cos^2\theta}$$

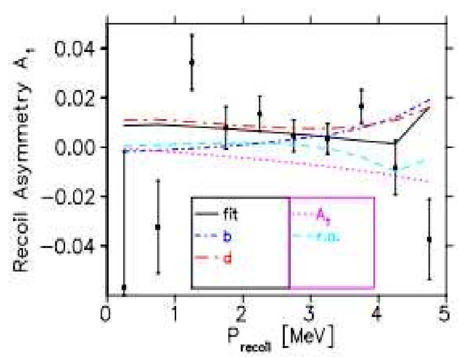
Insensitive to Right-Handed currents; constrains Tensor Interaction



Using recoil momentum information enhances the sensitivity and allows separation of SM recoil-order corrections (O. Aviv, MSc. Thesis, Tel Aviv University (2004)):

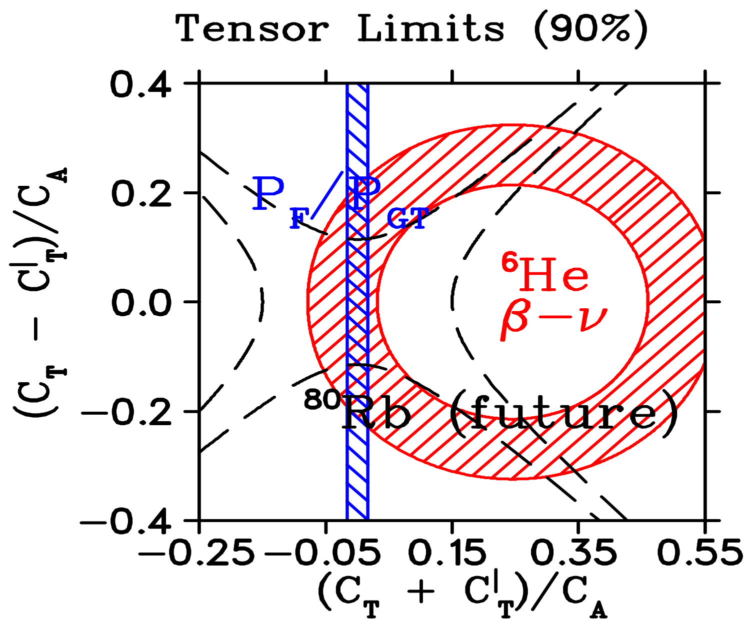
$$A_{\rm spin}(P_R) = \frac{(f_4(A_\beta + B_\nu) - f_7 b) P \cos\theta}{f_1 - f_6 b - f_2(a_{\beta\nu} + c'/3) + c'(f_3 + f_5 \cos^2\theta)}$$

$f_i(P_R)$ **: Calculated functions of recoil momentum**



Use polarized ^{80}Rb, $1^+ \rightarrow 0^+$ pure GT transition. P_{Recoil} from TOF to Shakeoff e^- MCP

$(A_\beta + B_\nu) = 0.015 \pm 0.029$ **arXiv: 0811.0052 [nucl-ex],**
J.R.A. Pitcairn *et al.*, **Phys. Rev. C79, 015501 (2009)**



Experimental precision better by an order of magnitude, BUT:

Constraints on Tensor Interaction dominated by theoretical uncertainties in Recoil-Order corrections

SUMMARY

- Studies of β decay of trapped radioactive nuclei provide constraints on the Standard Model
- Next generation experiments will provide tighter constraints, complementary to measurements with HE accelerators

$$
\begin{aligned}
\xi &= |M_F|^2(|C_S|^2+|C_V|^2+|C_S'|^2+|C_V'|^2)+|M_{GT}|^2(|C_T|^2+|C_A|^2+|C_T'|^2+|C_A'|^2) \\
a_{\beta\nu}\xi &= |M_F|^2(-|C_S|^2+|C_V|^2-|C_S'|^2+|C_V'|^2)+\frac{|M_{GT}|^2}{3}(|C_T|^2-|C_A|^2+|C_T'|^2-|C_A'|^2) \\
b\xi &= \pm 2Re[|M_F|^2(C_S C_V^*+C_S'C_V'^*)+|M_{GT}|^2(C_T C_A^*+C_T'C_A'^*)] \\
c\xi &= |M_{GT}|^2\Lambda_{J'J}(|C_T|^2-|C_A|^2+|C_T'|^2-|C_A'|^2) \\
A_\beta\xi &= 2\mathrm{Re}[\pm|M_{GT}|^2\lambda_{J'J}(C_T C_T'^*-C_A C_A'^*)+\delta_{J'J}|M_{GT}||M_F|\sqrt{J/(J+1)}(C_S C_T'^* \\
&\quad +C_S'C_T^*-C_V^*C_A'^*-C_V'C_A^*)] \\
B_\nu\xi &= 2\mathrm{Re}\{|M_{GT}|^2\lambda_{J'J}[\frac{m_e}{E_e}(C_T C_A'^*+C_T'C_A^*)\pm(C_T C_T'^*+C_A C_A'^*)] \\
&\quad -\delta_{J'J}|M_{GT}||M_F|\sqrt{J/(J+1)}\times[(C_S C_T'^*+C_S'C_T^*+C_V C_A'^*+C_V'C_A^*) \\
&\quad \pm\frac{m}{E_e}(C_S C_A'^*+C_S'C_A^*+C_V C_T'^*+C_V'C_T^*)]\} \\
D\xi &= 2\mathrm{Im}\{\delta_{JJ'}|M_F||M_{GT}|\sqrt{\frac{J}{J+1}}(C_S C_T^*+C_S'C_T'^*-C_V C_A^*-C_V'C_A'^*)\}
\end{aligned}
$$

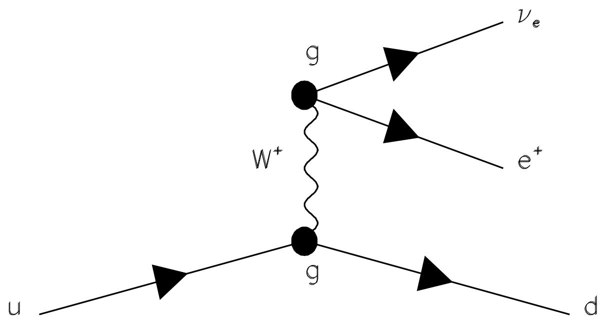
$$
\lambda_{J'J}=\begin{cases} 1, & J\to J'=J-1 \\ \frac{1}{J+1}, & J\to J'=J \\ -\frac{J}{J+1}, & J\to J'=J+1 \end{cases}
$$

$$
\Lambda_{J'J}=\begin{cases} 1, & J\to J'=J-1 \\ -\frac{2J-1}{J+1}, & J\to J'=J \\ \frac{J(2J-1)}{(2J+3)(J+1)}, & J\to J'=J+1 \end{cases}
$$

C_i: Interaction Amplitudes (complex)

$$
\begin{aligned}
C_V &= g_V(a_{LL} + a_{LR} + a_{RR} + a_{RL}) & C_V^{'} &= g_V(a_{LL} + a_{LR} - a_{RR} - a_{RL}) \\
C_A &= g_A(a_{LL} - a_{LR} + a_{RR} - a_{RL}) & C_A^{'} &= g_A(a_{LL} - a_{LR} - a_{RR} + a_{RL}) \\
C_S &= g_S(A_{LL} + A_{LR} + A_{RR} + A_{RL}) & C_S^{'} &= g_S(A_{LL} + A_{LR} - A_{RR} - A_{RL}) \\
C_T &= 2g_T(\alpha_{LL} + \alpha_{RR}) & C_T^{'} &= 2g_T(\alpha_{LL} - \alpha_{RR})
\end{aligned}
$$

g_i **: Hadronic Form Factors** a_{ij} **: Chirality coupling constants** i **:** ν j **: quark**



Standard Model: V - A, left handed

g_V **= 1,** g_A **= -1.27 (n decay)**

$a_{LL} = V_{ud}\frac{g^2}{8M_W^2} \cong 8 \cdot 10^{-6} GeV^{-2}$

$a_{ij}, A_{i,j}, \alpha_{i,j} = 0 \quad i, j \neq L, L$

$a_{\beta\nu} = \frac{y^2 - \frac{1}{3}}{y^2+1}, \quad y = \frac{C_V M_F}{C_A M_{GT}}$

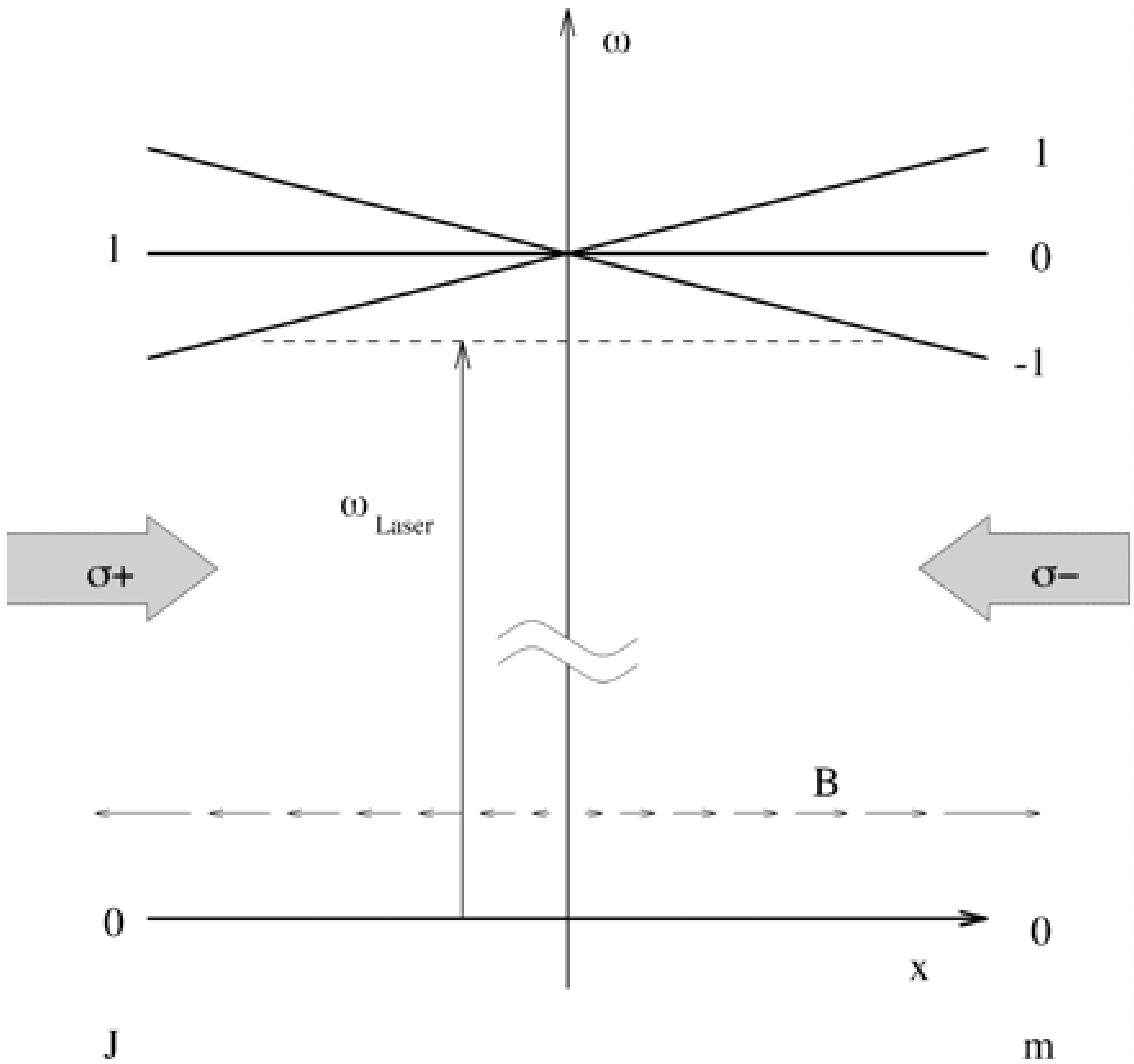
$b = 0$

$c = \frac{-\Lambda_{JJ'}}{1+y^2}$

$A_\beta = \frac{\mp\lambda_{JJ'} - 2\delta_{JJ'} y \sqrt{J/(J+1)}}{y^2+1}$

$B_\nu = \frac{\pm\lambda_{JJ'} - 2\delta_{JJ'} y \sqrt{J/(J+1)}}{y^2+1}$

$D = 0$


ω
1
1
0
-1
ω Laser
σ+
σ−
B
0
0
x
J
m