TRIUMF TRV in nuclear β decay: experimental opportunities

- **Intro**
  a few common techniques
  How are isobaric analog decays like neutron decay?

- **Experimental opportunities**

$R\vec{\sigma}_\beta \cdot \hat{\mathrm{J}} \times \frac{\vec{\mathrm{p}}_\beta}{E_\beta}$ ^{8}Li, ^{19}Ne

$D\hat{J} \cdot \frac{\vec{p_\beta}}{E_\beta} \times \frac{\vec{p_\nu}}{E_\beta}$ ^{19}Ne; ^{23}Mg/^{39}Ca; (^{37}K; ^{20}Na)

$E\vec{J} \cdot \vec{p_\beta} \times \vec{k_\gamma} \vec{J} \cdot \vec{k_\gamma}$ Spin-β-γ correlation ^{36}K

$\beta\nu\gamma$ ^{37}K

most quoting the literature for
(Final-state effects + some Phenomenology)

$\not{T}$, $\not{CP}$, and baryon asymmetry

Sakharov JETP Lett 5 24 (1967) used $\not{CP}$ to generate the universe's excess of matter over antimatter:

- **$\not{CP}$,**
- **baryon nonconservation, and**
- **nonequilibrium.**

But known $\not{CP}$ in the standard model is too small by 10^{10}, so we need more to exist

Caveats:

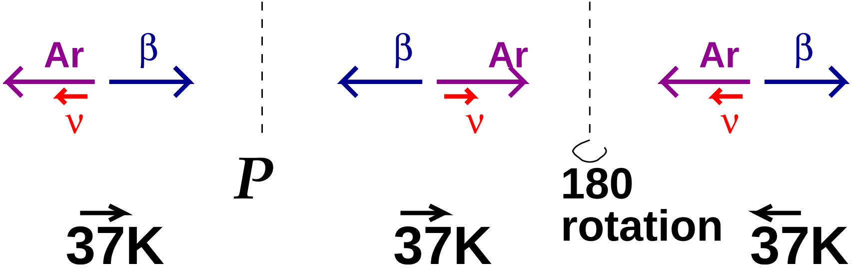
- can be done with $\not{CPT}$ (Dolgov Phys Rep 222 (1992) 309)
- We need more $\not{CP}$ in the early universe, not necessarily now

→ • We should look for $\not{CP}$ i.e. $\not{T}$ violation where we can

Decays: Parity Operation can be simulated exactly by Spin Flip

Under Parity operation *P*:

$\vec{r} \rightarrow -\vec{r}$ $\quad\quad$ $\vec{p} \sim \frac{d\vec{r}}{dt} \rightarrow -\vec{p}$ $\quad\quad$ $\vec{J} = \vec{r} \times \vec{p} \rightarrow +\vec{J}$



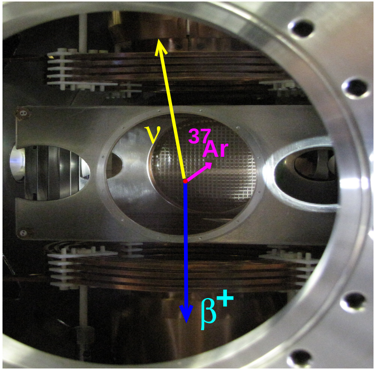
This is exact

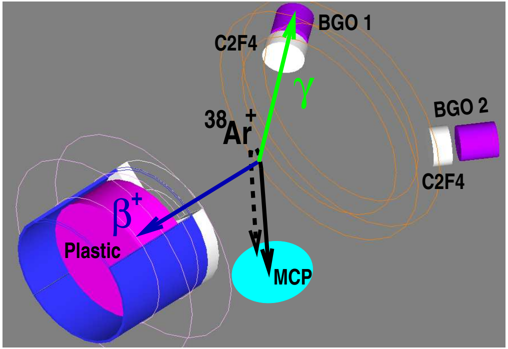
3-momentum $\not{T}$ correlation: Our example

When t → -t :

$\vec{r} \rightarrow \vec{r} \qquad \vec{p} \sim \frac{d\vec{r}}{dt} \rightarrow -\vec{p}$

$$\vec{p}_\nu \cdot \vec{p}_\beta \times \vec{p}_\gamma = -\vec{p}_{recoil} \cdot \vec{p}_\beta \times \vec{p}_\gamma \xrightarrow{t \rightarrow -t} \vec{p}_{recoil} \cdot \vec{p}_\beta \times \vec{p}_\gamma$$



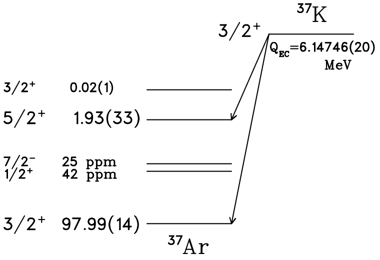


- We can test symmetry of apparatus with coincident pairs
- Not exact: outgoing particles interact → 'final-state' fake $\not{T}$

^{37}K isobaric mirror decay: a 'heavy neutron'?

$\Rightarrow A_\beta[SM]$ = -0.5706$\pm$0.0007

Dominant uncertainty is exp. branching ratio



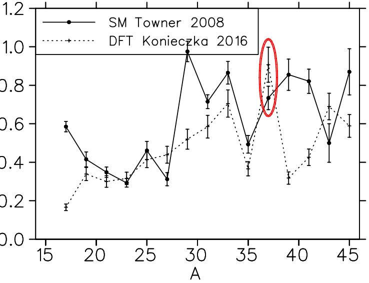
1st-order recoil-order from E&M moments:

Induced tensor $d_1 \approx 0$ for isobaric mirror

Small $\mu \Rightarrow$ small weak magnetism

Recoil-order + Coulomb + finite-size corrections $\Rightarrow$

$\Delta A_\beta \approx -0.0028\ (E_\beta/E_0)$ Holstein RMP 1975

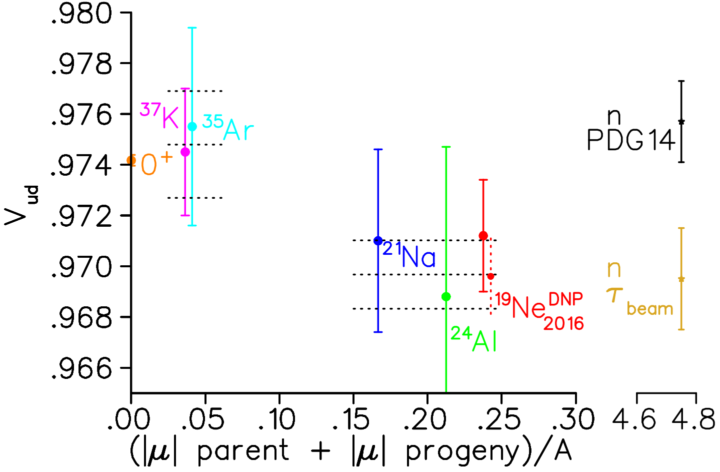


Isospin mixing contributes 0.0004 uncertainty from shell model (10%)

DFT for isospin mixing has improved functional for A$\sim$37

Using weighted average for δ_C would $\Rightarrow$ 0.0004 $\rightarrow$ 0.0005

CVC test in nuclei with nonzero spin



$A_\beta \Rightarrow$ GT/F

Then $\mathcal{F}t$ of ^{37}K $\Rightarrow V_{ud}$

- **Assuming isospin mixing test is ok Naviliat-Cuncic, Severijns PRL 102 142302 (2009)**
- **Salam and Strathdee Nature 1974: phase transitions at very high B fields could drive $V_{ud} \rightarrow 1$**

Hardy Towner PLB 1975: ^{35}Ar A_β controversy.

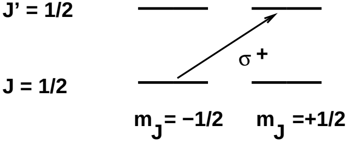
^{19}Ne Broussard DNP 2016

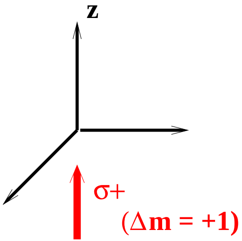
How to spin-polarize a nucleus with a laser

Polarization of nuclei by Optical Pumping

Biased random walk

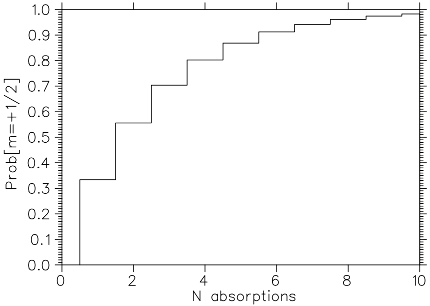
Simple example:





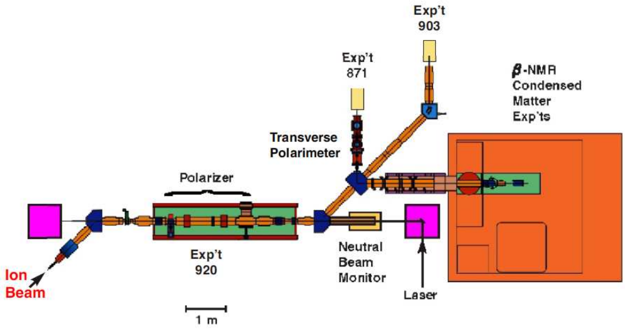
$P(m=1/2) = 1 - (2/3)^N$ after N steps

Need 12 photons absorbed to get to 99% of maximum.



TRIUMF Laser-Polarized beam at TRIUMF/ISAC

C.D.P. Levy et al. / Nuclear Physics A 746 (2004) 206c–209c



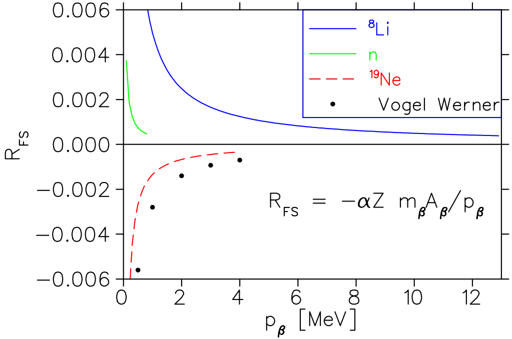
- 50-70% polarization, 20-50% efficient Re-stripped +1 beam deliverable to several beamlines
- Used for aligned ^{20}Na β correlation (2nd-class current comparison with ^{20}F) K. Minamisono PRC 84 055501 (2011)

^{8}Li *R*, Jiro Murata, Rikkyo U.

TRV possibilities include ^{36}K *E* and ^{20}Na β-delayed α energy shift (Clifford PRL 50 (1983) 23)

R final-state effects

$$R\vec{\sigma}_\beta \cdot \hat{\mathbf{J}} x \vec{\mathbf{v}}_\beta \overset{t \to -t}{\to} -R\vec{\sigma}_\beta \cdot \hat{\mathbf{J}} x \vec{\mathbf{v}}_\beta$$



Final-state effects Jackson Treiman Wyld NPA 1957

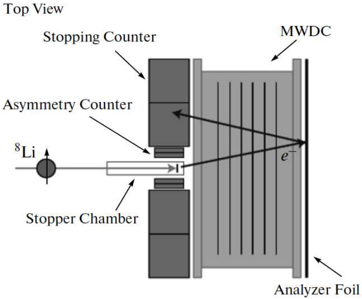
$$R_{\mathrm{fs}} = -\frac{\alpha Z_{\mathrm{final}} m_\beta}{p_\beta} A_\beta$$

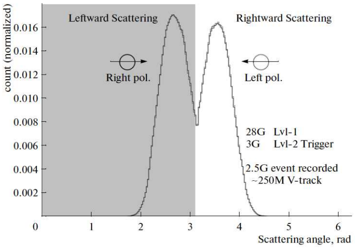
Vogel and Werner 1983: radiative and other corrections substantial for ^{19}Ne

PSI ***R*** = -0.2±4.0 × 10^{-3} ^{8}Li, Sromicki PRC 53 (1996) 932

R_{TRV} = -0.9±4.0 × 10^{-3}

Mott scattering Time reversal Violation progress





$$R\vec{\sigma}_\beta \cdot \hat{\mathbf{J}} \times \vec{\mathbf{v}}_\beta \overset{t\to -t}{\longrightarrow} -R\vec{\sigma}_\beta \cdot \hat{\mathbf{J}} \times \vec{\mathbf{v}}_\beta$$

Totsuka et al Phys Part Nuclei 45 244 (2014) Small false asymmetry in rectangular geometry

→ a more symmetric cylindrical geometry, finished data-taking Dec 2017

→ OtherSlides from Jiro Murata, Rikkyo University:

R in R-parity violating SUSY: Multi-parameter constraints

N. Yamanaka, T. Sato, T. Kubota JHEP12(2014)110

	d_p	d_d	$d_{\rm He}$	$d_{\rm Rn}$	$d_{\rm Ra}$	$d_{\rm Fr}$	R
Max.	1.7×10^{-25}	1.1×10^{-22}	7.3×10^{-23}	9.5×10^{-26}	4.1×10^{-23}	3.1×10^{-24}	2.4×10^{-6}
x_1	-0.15	0.15	0.15	0.15	-0.15	0.15	0.15
x_2	-9.2×10^{-2}	9.1×10^{-2}	2.2×10^{-3}	-0.11	-9.3×10^{-2}	-0.12	-0.11
x_3	-1.8×10^{-4}	1.8×10^{-4}	2.0×10^{-5}	-1.8×10^{-4}	-1.8×10^{-4}	-1.8×10^{-4}	-1.8×10^{-4}
x_4	-1.1×10^{-2}	1.1×10^{-2}	-6.7×10^{-4}	-1.1×10^{-2}	-1.1×10^{-2}	-1.1×10^{-2}	-1.1×10^{-2}
x_5	0.19	-0.19	-4.9×10^{-3}	0.19	0.19	0.19	0.19
x_6	-5.0×10^{-2}	5.0×10^{-2}	5.0×10^{-2}	-5.0×10^{-2}	-5.0×10^{-2}	-5.0×10^{-2}	-5.0×10^{-2}
x_7	-5.5×10^{-2}	5.5×10^{-2}	5.5×10^{-2}	-5.5×10^{-2}	-5.5×10^{-2}	-5.5×10^{-2}	-5.5×10^{-2}
x_8	-8.9×10^{-3}	-8.9×10^{-3}	-8.9×10^{-3}	8.9×10^{-3}	8.9×10^{-3}	8.9×10^{-3}	8.9×10^{-3}
x_9	3.0×10^{-2}	-3.0×10^{-2}	-3.0×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	3.0×10^{-2}
x_{10}	-0.15	0.15	0.15	-0.15	-0.15	-0.15	-0.15

Table 11. Maximal predictions of the EDMs of the proton, deuteron, ^{3}He nucleus, ^{211}Rn, ^{225}Ra, and ^{210}Fr atoms, and the R-correlation of the neutron beta decay, within the constraints of the ^{205}Tl, ^{199}Hg, ^{129}Xe, YbF, ThO, and neutron EDM experiments. Coordinates x_i maximizing the observables are also shown. The EDMs are expressed in unit of e cm. The sparticle mass $m_{\rm SUSY}$ has been taken to be 1 TeV.

"Linear programming" identifies maxima for many linear equations 6 EDM experiments, 10 parameters (sums of SUSY bilinear coefficients) $\Rightarrow$

$R < 2 \times 10^{-6}$

R is sensitive mainly to $Im(\lambda_{i11}\lambda'^{*}_{i11})$, so could help interpret EDM's sensitive to several observables... but this sensitivity is needed

R and *N* Valuable test

Kozela PRL 102 172301 (2009): S.M. prediction for $N \propto R$'s FS effects:

$N\vec{\sigma}_\beta \cdot \vec{\mathrm{J}}$ $\quad R\vec{\sigma}_\beta \cdot \vec{\mathrm{J}} \times \vec{\mathrm{p}}_\beta$

$$N\xi = 2\,\mathrm{Re}\Big\{ |M_{GT}|^2 \lambda_{J'J} \Big[\frac{1}{2}\frac{\gamma m}{E_e}(|C_T|^2+|C_A|^2+|C'_T|^2+|C'_A|^2) \pm (C_T C_A^* + C'_T C'^*_A)\Big] + \delta_{J'J} M_F M_{GT} \sqrt{\frac{J}{J+1}} \Big[(C_S C_A^* + C_V C_T^* + C'_S C'^*_A + C'_V C'^*_T) \pm \frac{\gamma m}{E_e}(C_S C_T^* + C_V C_A^* + C'_S C'^*_T + C'_V C'^*_A)\Big]\Big\} \quad \text{(A.14)}$$

$$R\xi = |M_{GT}|^2 \lambda_{J'J} \Big[\pm 2\,\mathrm{Im}\,(C_T C'^*_A + C'_T C_A^*) - \frac{\alpha Z m}{p_e} 2\,\mathrm{Re}(C_T C'^*_T - C_A C'^*_A)\Big] + \delta_{J'J} M_F M_{GT} \sqrt{\frac{J}{J+1}} \Big[2\,\mathrm{Im}\,(C_S C'^*_A + C'_S C_A^* - C_V C'^*_T - C'_V C_T^*) \mp \frac{\alpha Z m}{p_e} 2\,\mathrm{Re}\,(C_S C'^*_T + C'_S C_T^* - C_V C'^*_A - C'_V C_A^*)\Big]. \quad \text{(A.16)}$$

N is a bkg for ***R*** if there is off-axis polarization

^{19}Ne $D = (1 \pm 6) \times 10^{-4}$ Hallin et al. PRL 52 (1984) 337

Dedicated geometry– accurate absolute angular correlations for efficiency

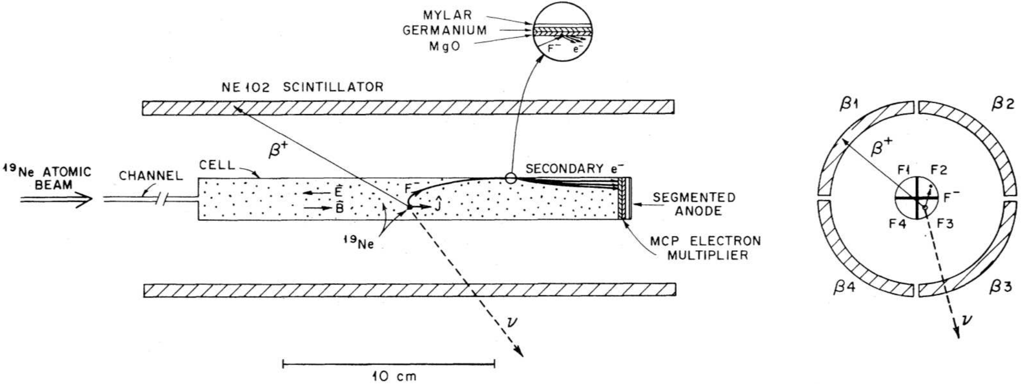
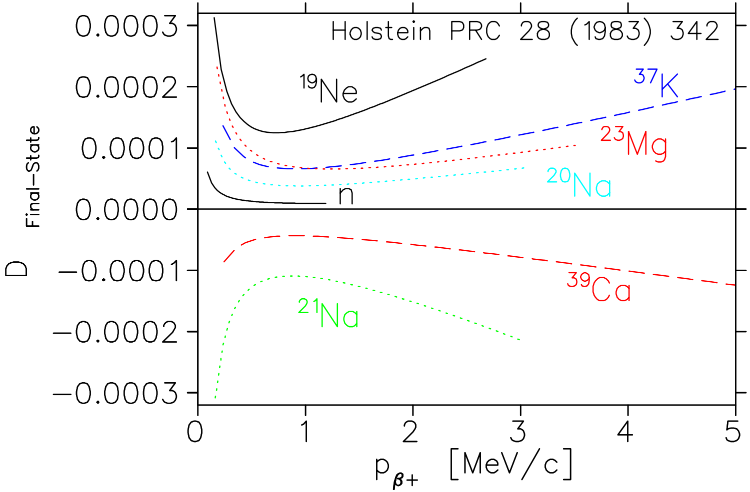


FIG. 1. Schematic illustration of the cylindrical cell and the detector system. Polarized ^{19}Ne, which enters the cell through a long narrow channel, fills the entire cell (dots). A uniform magnetic field maintains the polarization along the cell axis. In a typical decay the positron passes through the thin wall of the cell to one of four plastic scintillators (β_1 through β_4). The F^- recoil ion is accelerated along the cell axis by an electric field. The ion strikes the inside surface emitting secondary electrons which are accelerated into an electron multiplier segmented in four parts (F_1 through F_4).

D and final-state effects

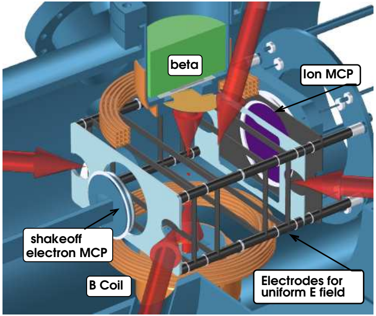
Holstein PRC 28 (1983) 342; dependence on Z and weak magnetism

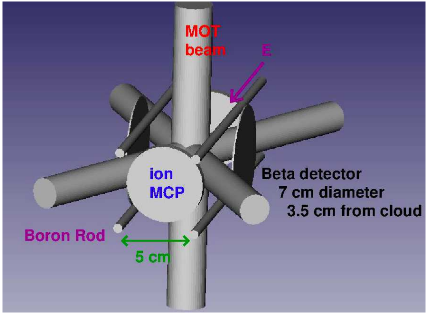


→ OtherSlides from Pierre Delahaye, LPC Trap:

TRINAT and D: future?

^{37}K P=99.1$\pm$0.1% measured atomically (Fenker NJP 2016)
Electric fields uniform for accurate angular correlations
To compete would require a dedicated geometry
emiT (neutron) 2011: D= -0.96 $\pm$ 1.89 $\pm$ 1.01 $\times$ 10^{-4}





This is a cartoon
without an error budget

Dedicated geometry:
stats 1x10^{-4} in 2 weeks
Would need transparent β detectors to increase dΩ further
Isolate UHV with Kapton $>$ 85% transmission for 767 nm
We have a MOT with 100 nm Au on 4μm Kapton mirrors

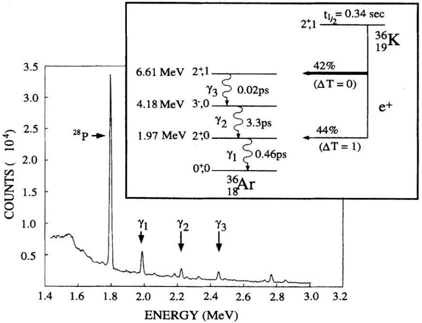
some D phenomenology

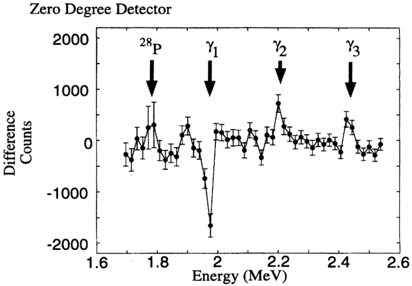
- **Ng and Tulin PRD constraints from EDM's (and from non-TRV experiments, like atomic parity violation constraints on leptoquarks) on the GT-Fermi interference phase**

- **El-Menoufi, Ramsey-Musolf, and Seng, Phys Lett B 765 (2017) 62 considers D's dependence on C_s, C_t coupling to wrong-handed neutrinos, relatively weak constraints from other TRV observables.**
  But tight constraints from p+p $\rightarrow$ e$^-$ + MTE which measure sum of abs(squared) of everything

- **Are there any models possible mediated by light weakly coupled (yet electrically charged) bosons?**

E spin β γ correlations



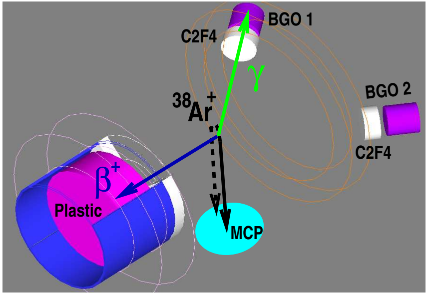


A. Young PRC 52 (1995) R464 Substitutes efficient γ-ray detection for nuclear recoil detection

→ OtherSlides from Kei Minamisono, MSU/NSCL

Time-reversal violation $\not{T}$ in radiative β decay: exp. progress

- $\not{T}$ **Motivation**
- **Our geometry and simulation for $\beta\nu\gamma$ correlation**
- **Symbiotic test ^{92}Rb $0^{-} \rightarrow 0^{+}$**



TRIumf Neutral Atom Trap:

TRIUMF
A. Gorelov
J.A. Behr

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TEL AVIV UNIVERSITY
D. Ashery

Support: NSERC, NRC through TRIUMF, US DOE, Israel Science Foundation

3-momentum $\not{T}$ correlations: Other examples

Don't depend directly on spin, so only generate EDM's in higher order

- **Medium and high-energy TRV 3-momentum correlations:**

  $K^- \to \pi^0 e^- \bar{\nu}_e \gamma$ INR Moscow 2007, $A_{TRV} = -0.015 \pm 0.021$
  Three progressively better calculations of the final-state effects were done (Khriplovich+Rudenko 1012.0147 Phys Atomic Nuclei 2011)

- **3-momentum correlations (no γ) at LHCb and BABAR, 0 ± 0.003 (Martinelli arXiv 1411.4140)**

- **General formalism for triple product momentum asymmetries Bevan 1408.3813**

$\not{T}$ in $\pi^\pm \to e^\pm \nu e^+ e^-$ Proposed but never done
[Flagg Phys Rev **178** 2387 (1969)]

Ours would be unique measurement in 1st generation of particles

TRIUMF $\gamma\beta\nu\not{T}$: A model

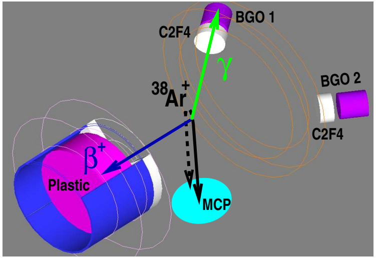
Harvey Hill Hill PRL 99 261601 combine in SM QCD+electroweak interaction in the nucleon's $\mathcal{L}$

Gardner, He PRD 87 116012 (2013) reduce this to

$$\mathcal{L} = -\frac{4c_5}{m_{\text{nucleon}}{}^2}\frac{eG_F V_{ud}}{\sqrt{2}}\epsilon^{\sigma\mu\nu\rho}\bar{p}\gamma_\sigma n\bar{\psi}_{eL}\gamma_\mu\psi_{\nu L}F_{\nu\rho}$$

which upon interference with S.M. gives $\not{T}$ decay contribution [Needs vector current!] $\rightarrow$

$$|\mathcal{M}_{c5}|^2 \propto \frac{Im(c_5 g_V)}{\mathrm{M}^2}\frac{E_e}{p_e k}(\vec{p_e} \times \vec{k_\gamma}) \cdot \vec{p_\nu}$$



new physics $M \sim$ MeV

- $\not{T}$ 250x larger in ^{38m}K decay than neutron
- final state fake effect 8x10^{-4}

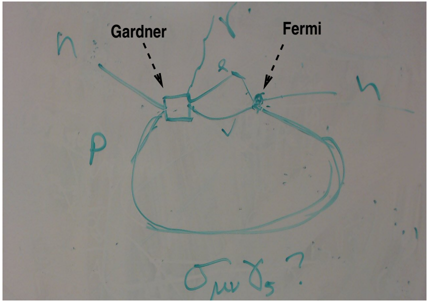
- n $\rightarrow$ p $\beta\nu\gamma$ branch (Nico Nature 06, Bales PRL 16) $\Rightarrow$

$\frac{\mathrm{Im}(c_5)}{M^2} \leq 8 MeV^{-2} \Rightarrow$ Asym can be ~ 1

Bales b.r. = $(3.35 \pm 0.16) \times 10^{-3}$, 1.7 σ higher than theory 3.08×10^{-3}

TRIUMF EDMs and $\not{T}$ radiative β decay amend **

No spin involved, so different physics at lowest order, but



Ng, Vos private comm.:
'Im(c_5)' interaction
+ s.m. β decay
$\rightarrow$ n EDM at 2 loops

'Naive Dimensional Analysis':

$$d_n \sim \frac{Im(c_5) G_F e}{M^2} \frac{G_F m_n^5}{(16\pi^2)^2} \sim \frac{10^{-22} e-cm}{M^2} [\mathrm{MeV}^{-2}]$$ **

$d_n[\mathrm{exp}] < 3 \times 10^{-26}$e-cm
(Baker 2006 PRL)

null n EDM $\Rightarrow \frac{Im(c_5)}{M^2} < 3 \times 10^{-4} [\mathrm{MeV}^{-2}] \rightarrow 10^{-3}$ asym **

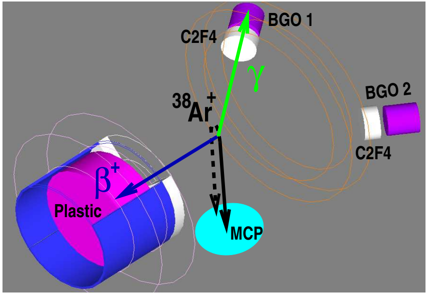
We could still reach this sensitivity and measure this physics directly

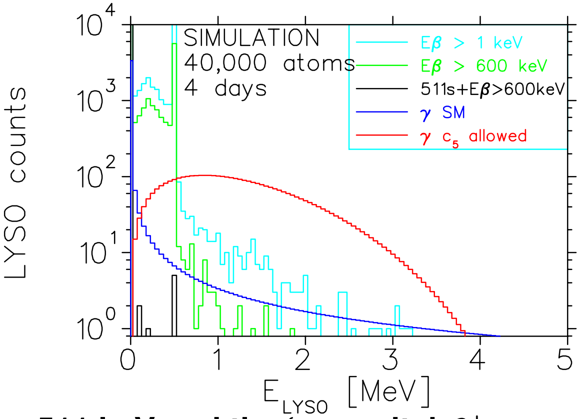
[Some $\gamma\beta\nu$ interactions make at 1 loop a neutron EDM]

** Loop integral momenta must stay below EFT scale M, so using m^5_{nucleon} likely overestimates by orders of magnitude

Generic phase space for $\gamma\beta\nu\not{T}$

- **Classical bremsstrahlung $\propto 1/E_\gamma$**
- **Any time-reversal violating interaction involves β, ν and γ and produces a 4-body phase space $\propto E_\gamma(Q - E_\gamma)^3$**

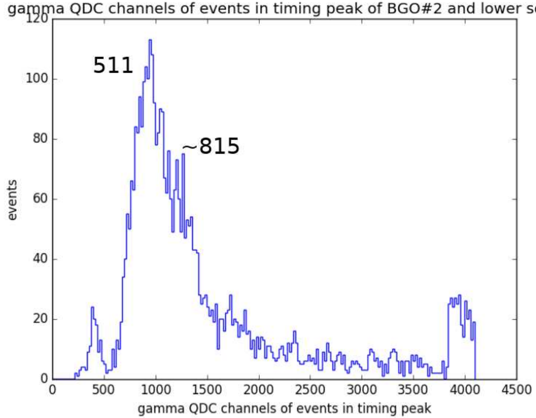


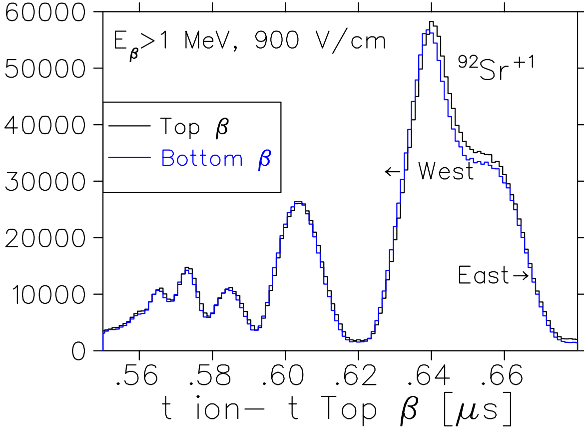


Sensitivity to $\sim$ 5% of classical bremsstrahlung rate

We are concentrating on $E_\gamma > 511$ keV and the 'opposite' β^+

Test with ^{92}Rb $0^- \rightarrow$ ^{92}Sr 0^+ + $\beta^-\nu\gamma$





Online β-γ doubles:

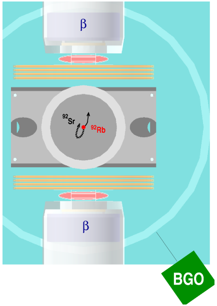
511 keV from E&M showers

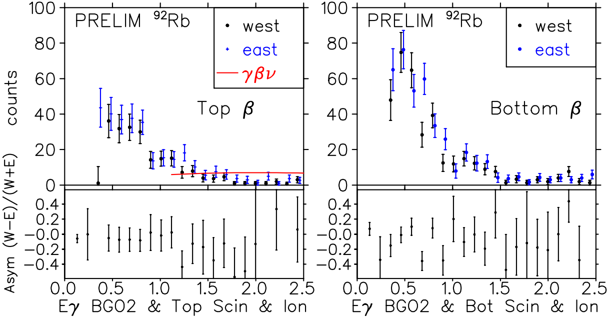
Shoulder of 3-6% 815 keV γ from ^{92}Rb decay

East and west-going ions

Ion TOF spectrum similar for top and bottom β

TRIUMF Test with ^{92}Rb $0^- \rightarrow$ ^{92}Sr 0^+ + $\beta^-\nu\gamma$





- γ spectrum in coincidence with β^- and ions ‘west’ vs. ‘east’.
- 5x10^6 ion-β coincidences: Sensitivity to few % γ branch

- Top and bottom β + GEANT4 may disentangle radiative γ, showers (511!), discrete 815 keV γ’s and $\gamma\beta\nu$

No vector current, so no c_5 interaction:
Sensitive to pseudoscalar $\not{T}$?
The pseudoscalar quark $\rightarrow$ nucleon form factor is 350 (Gonzalez-Alonso and Camalich PRL 2014)

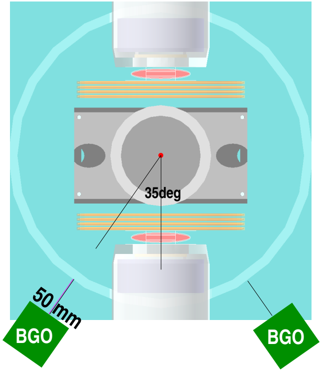
TRIUMF $\not{T}$ $\gamma\beta\nu$: Experimental progress

- New observable, sensitive to MeV-scale $\not{T}$
  Ours would be a unique measurement in
  1st generation of particles

Complementary to $K^- \rightarrow \pi^0 e^- \bar{\nu}_e \gamma$
INR Moscow 2007, $A_{TRV} = -0.015 \pm 0.021$

- Adding γ's to TRINAT's $\beta\nu$ detection

Focus on $E_\gamma > 0.511$ MeV and 'opposite' β^+
^{92}Rb test: possible sensitivity to $\not{T}$ pseudoscalar



- Vector current mechanism of Gardner and He:

Projection for 40,000 atoms $^{37,38\mathrm{m}}$K trapped and a week:
If new physics has 3% branch, 5 days for 1% on $\not{T}$ asym.
Sensitivity to 5% of SM bremsstrahlung $\rightarrow$ 10% on $\not{T}$ asym

TRIUMF Summary: TRV in nuclear β decay: experimental opportunities

Analysis Ongoing: *R* ^{8}Li could reach 10^{-4} see Murata (Rikkyo U.) slides

Project started for *D* ^{23}Mg^{+} 10^{-4} JYFL and 10^{-5} at SPIRAL2 see Delahaye slides

Optically pumped Paul trap

Conceivable: *E* ^{36}K See A. Young PRL and Minamisono slides

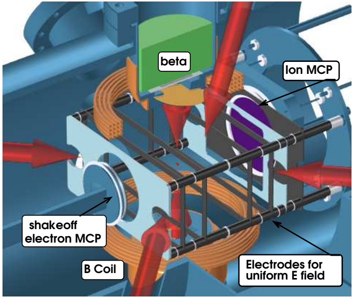
Radiative β decay of Gardner and He: symbiotic experiment at TRIUMF

Theory questions: Are there light degrees of freedom that evade p+p $\rightarrow$ e^{-}+MTE ?

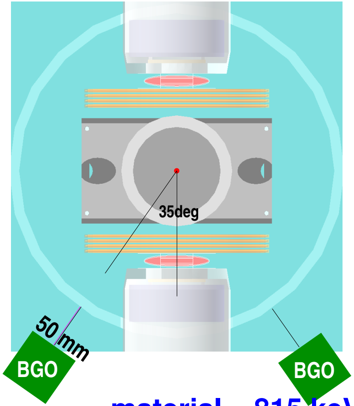
Do 2nd-class currents (break G-parity or isospin in 1st generation) matter?

Are there any physics advantages to heavier nuclei besides Coulomb term in non-TRV experiments?

Geometry: simplest addition to TRINAT



Coincidence with upper β^+ detector →



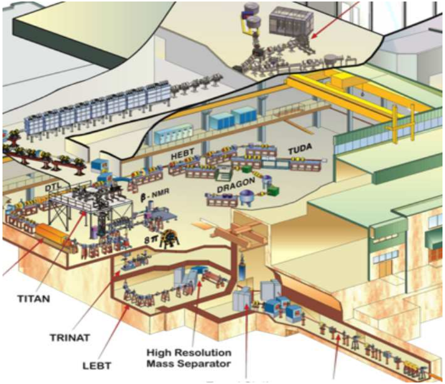
- **Added BGO detectors with SiPM readout**

Tested symbiotic to ^{92}Rb ν spectrum Sep 2018 [J. McNeil CN.00005 now Kohala 4]

Photopeak/total:

	material	815 keV (3% ^{92}Rb)	2.17 MeV (2% ^{37}K)
10 KHz	LYSO	0.59	0.28
Best Z	BGO	0.60	0.34
Bright, low Z	NaI	0.26	0.10
90ns, 50K γ/MeV	GAGG	$>$ NaI	$>>$ NaI

TRIumf Neutral Atom trap at ISAC

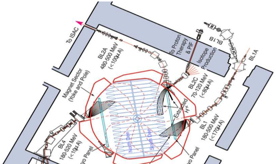


^{37}K 8x10^{7}/s

TiC target
1750^{o}C

70 μA
protons

main TRIUMF cyclotron
'world's largest'
500 MeV H^{-} (0.5 Tesla)

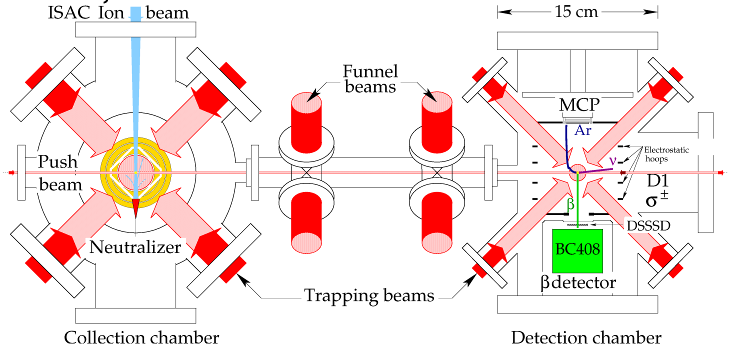


TRINAT efficiency, ISAC yields for S1603

ISAC 8×10^7/s ^{37}K from TiC 2014
0.5 Zr catcher release 900°C
5×10^{-4} Collection
0.65 Decay before transfer
0.75 Transfer efficiency
$\rightarrow$ 10,000 atoms ^{37}K demonstrated

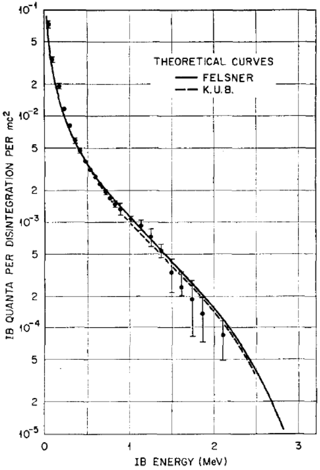
0.01 β detection efficiency
0.15 Ar ion fraction
0.5 MCP ion efficiency
0.8 Counting duty cycle
(Polarized + Unpolarized)
ISAC 4x more ^{38m}K from TiC

J.A. Behr et al. Hyperfine Interactions 225 115 (2014)
T.B. Swanson et al. JOSA B 15 2641 (1998)



Past radiative nuclear β^- decay experiments

^{6}He Bienlein and Pleasonton NP 1965



^{35}S

vector current $\mathcal{O}(10^{-2})$

Boehm and Wu PR 93 518 (1954)

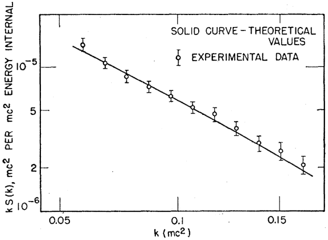
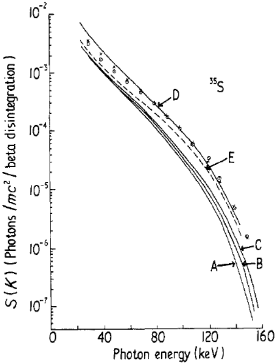


FIG. 3. Internal bremsstrahlung of S³⁵.

For axial vector current

Powar and Singh JPG 2 43 (1976)



5-10% discrepancies allowed

$\not{T}$ in radiative β decay and EDMs

Dekens, Vos 1502.04629: dim 6 operators at TeV scale

$$\mathcal{L}_6^{\rm eff} = -\frac{8ic_w}{gv^2} V_{ud}\,\mathrm{Re}\,C_{\varphi\tilde{W}B}(\Lambda)\,\varepsilon^{\mu\nu\alpha\beta}(\bar{u}_L\gamma_\mu d_L)(\bar{e}_L\gamma_\nu\nu_L)F_{\alpha\beta}$$

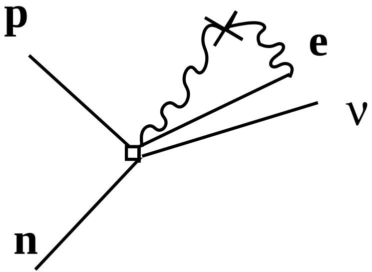
$\rightarrow 10^{-10}$ asymmetries if constants $\sim$ 1.
Also generates EDMs $\Rightarrow$ constants $\sim$ 0.01
So TeV-scale general dim 6 ops can make $\not{T}$ $\gamma\nu\beta$ and EDMs, but don't make measureable nuclear radiative β decay; effects $\sim p^2_{\rm lepton}/\mathrm{scale}^2$.

The QCD-like MeV-scale example of Gardner and He is tuned to maximize contribution to neutron β decay and avoid other experiments. E.g. direct searches by colliders are masked by jets.
EDMs constrain the Gardner term anyway in 2 loops (see above)

Vector current needs β^+ emitter

- β^- decays with vector current:
  n, ^{3}H, (not easy)
  'isospin-forbidden Fermi' amplitudes with $log(ft) \sim 5-6$ (e.g. ^{35}S)
  But isobaric analogs usually lie high in excitation for β^-
  E.g. ^{24}Na $4^+ \rightarrow$ ^{24}Mg 4^+, $log(ft) = 6$ (famous for the analog transition from ^{24}Al), feeds 2 subsequent γs so does not help.
  ^{92}Rb $0^- \rightarrow$ 0+ is 'first-forbidden G-T' which does not have the vector current,
  nor does first-forbidden unique ^{42}K $2^- \rightarrow 0^+$
  Other first-forbidden can have vector current contributions times some other operator (^{93}Rb) but these have a lot of γs
- The interference with SM term requires this vector current to produce the Gardner-He term.

TRIUMF D $\vec{I}\cdot\vec{v}_\beta\times\vec{v}_\nu$ and $\gamma\beta\nu$TRV amend**



K. Vos, W. Dekens (private communication)
One loop correction produces large D observable

'Naive Dimensional Analysis'

$D_{c5} \approx \mathcal{I}\frac{\alpha}{4\pi}4M_N^2\frac{\mathrm{Im}(c_5)}{M^2}$ ** $\Rightarrow$

$\frac{\mathrm{Im}(c_5)}{M^2} \lesssim 1/\mathcal{I}\ \ D_{c5}\times 10^{-3}[MeV^{-2}]$

^{37}K wins by $p^2 \sim 25$ w.r.t neutron, and if M^2 is tuned we could win by 25 more

But this is still a tight constraint, depending on whether $\mathcal{I}$ is 0 or infinity

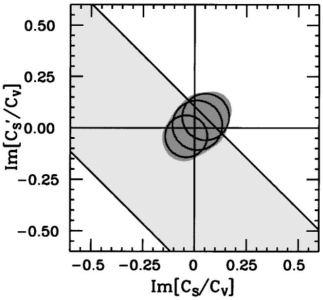
** Loop integral momenta must stay below EFT scale M, so using m^5_{nucleon} likely overestimates by orders of magnitude

Limits on TRV from non-TRV

β-ν correlation in ^{32}Ar, $^{38\mathrm{m}}$K, $\mathbf{0^+ \rightarrow 0^+}$

$$a = \frac{2 - |\tilde{C}_S|^2 - |\tilde{C}_S'|^2 + 2Z\alpha m/p\,\mathrm{Im}(\tilde{C}_S + \tilde{C}_S')}{2 + |\tilde{C}_S|^2 + |\tilde{C}_S'|^2}$$

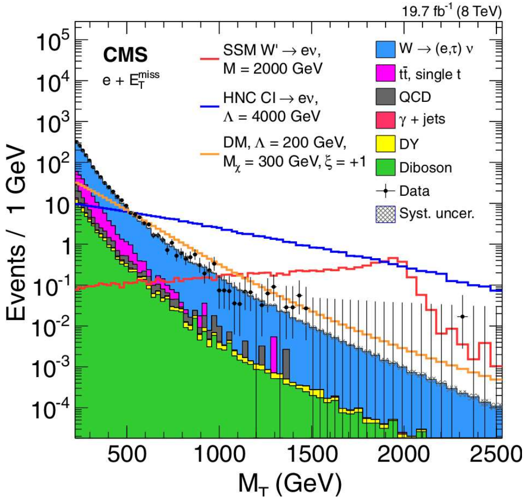
Coulomb correction gives sensitivity to TRV scalars competitive with ***R*** in ^{19}Ne
Schneider PRL 51 1239 (1983)



$\boldsymbol{p + p \rightarrow e^- + MTE}$ indirectly limits $\boldsymbol{C_S}$'s from high-energy EFT's at limits ~ 0.01

Are there any light charged degrees of freedom still possible?

Quasi-direct limits from high-energy colliders



E.g. Left-Right symmetric models
Extra W' with heavier mass, couples to ν_R

Along with peak searches:
LHC8 $\sigma[p + p \to e + \text{invisible}]$
Just like $n \to p + e + \nu$
CMS PRD 91 92005
Naviliat-Cuncic $\to$
Gonzalez-Alonso AnDP 2013
(Cirigliano JHEP 2013)
2 events expected, 1 seen
(later Bhattacharya PRD 94 054508
(2016) combined ATLAS, CMS.)

Following are contributions on
R status courtesy Jiro Murata, Rikkyo University
D plans from LPCTrap Pierre Delahaye,
E thoughts from Kei Minamisono, MSU/NSCL

THE MORA PROJECT

Matter’s Origin from the RadioActivity of trapped and laser oriented ions

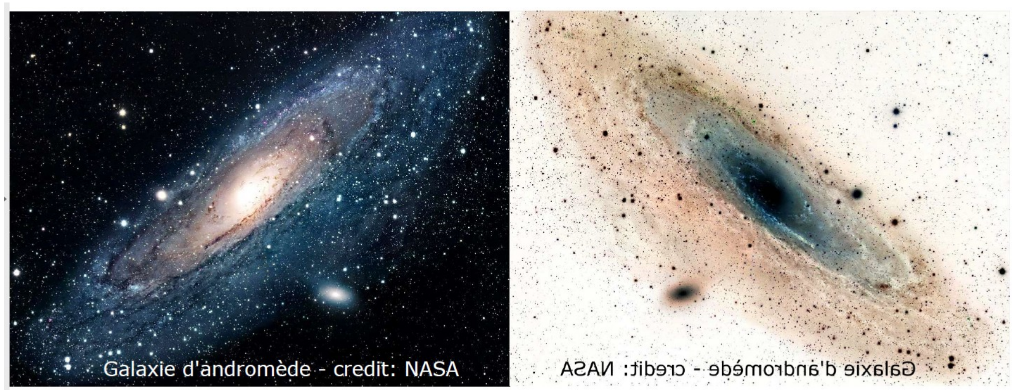
Pierre Delahaye for the MORA collaboration

Precision measurement of the triple correlation *D*

$$D\frac{\vec{J}\cdot(\overrightarrow{p_e}\times\overrightarrow{p_\nu})}{J(E_eE_\nu)}$$

A non-zero *D* can arise from CP violation

- CP violation observed in the K and B - meson decays is not enough to account for the large matter – antimatter assymetry
- T-odd correlations in beta decay (*D* and *R*) and n-EDM searches are sensitives to larger CP violations by 5 to 10 orders of magnitude



See P. Herczeg, Prog. Part. Nucl. Phys. 46 (2001) 413.

Below 10^{-4}, Final State Interactions mimic a non zero correlation

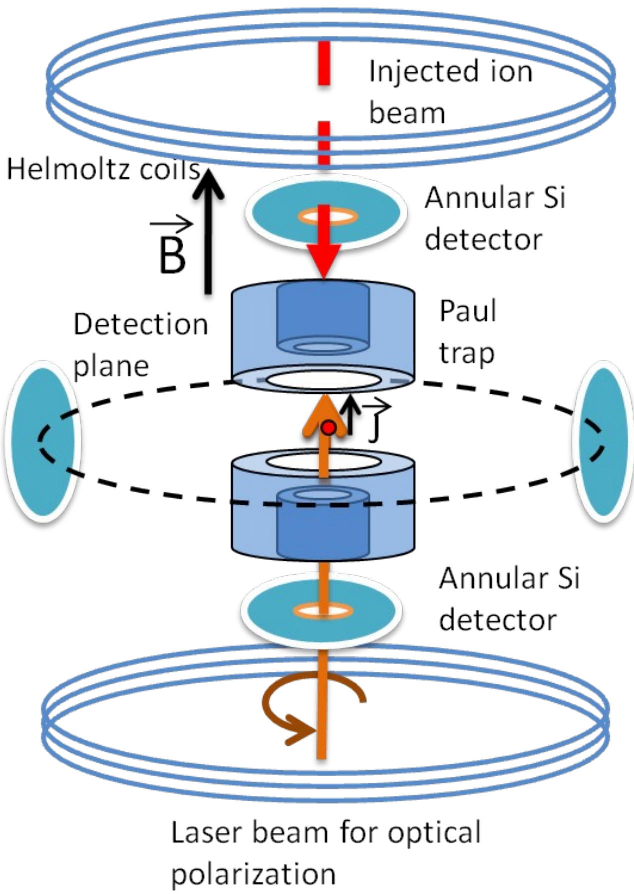
***D* correlation measurement to the 10^{-5} level with some beam, laser and trapping R&D**

- Best measurement so far D_n<2 10^{-4}
- Complementary probe to search for New Physics with nEDM and LHC searches
- First approach /probe of D_{FSI} for ^{23}Mg

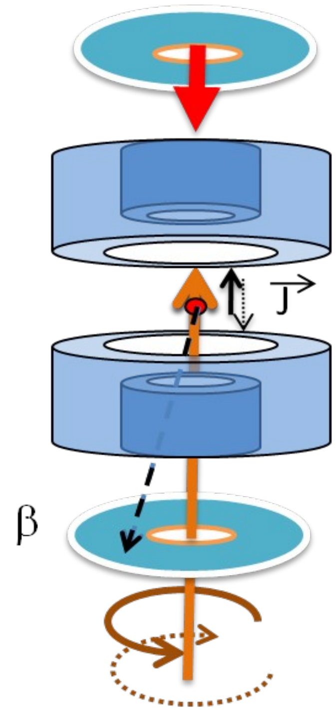
D correlation measurement setup

In trap optical polarization

$^{23}Mg^{+}$ as first candidate



Along the trap axis

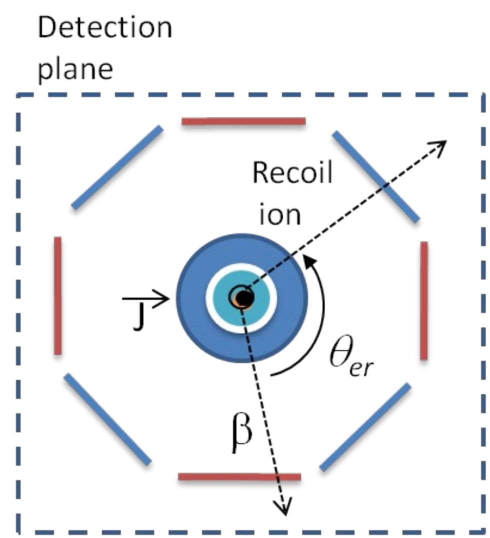


A_β correlation

Polarization degree

Azimuthal plane

Most sensitive plane to *D*!

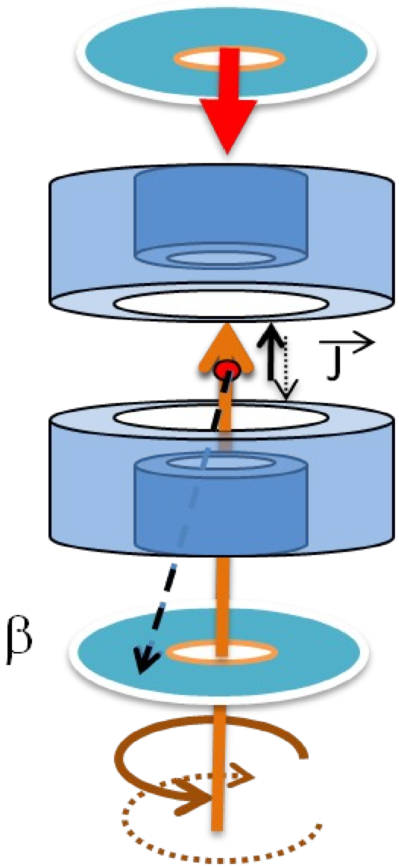


emiT – like detection setup

D correlation

Monitoring of polarization

THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY



P measurement

On-line monitoring of the polarization

A_β measurement

$$\frac{N^{\uparrow}_{\beta^+} - N^{\downarrow}_{\beta^+}}{N^{\uparrow}_{\beta^+} + N^{\downarrow}_{\beta^+}} \propto A_\beta \cdot P \qquad A_\beta \frac{\langle \vec{J} \rangle}{J} \cdot \frac{\vec{p_e}}{E_e}$$

Remember: C. S. Wu et al., Phys Rev 105(1957)1413

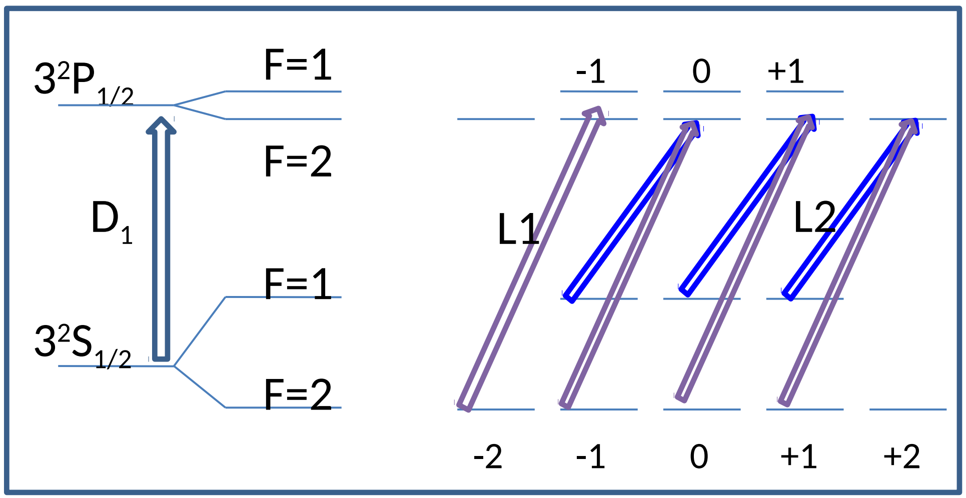
Extended interaction time with laser light
✉ Very high polarization degree
>90%: enough for the measurement of *D*!

RÉGION NORMANDIE

Optical pumping

- The nuclear spin I interacts with the atomic one J ✉ F=I+J
- σ+ or σ- light to scan the hyperfine structure forces ions in the m_F=±F state

^{23}Mg hyperfine structure F= I+J

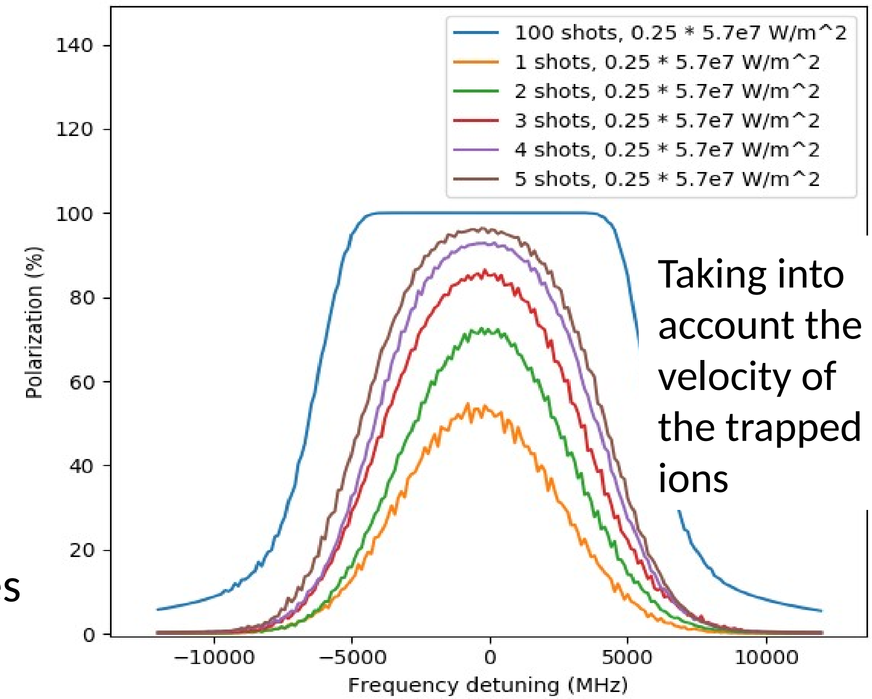


L1+L2 lasers excited using trippled Ti:Sa laser pulses

λ~280nm σ+ polarization

Transition probabilities: numerical simulations

R. de Groote, X. Fléchard and W. Gins



Collisions with He atoms (no spin) do not depolarize

With the power available at JYFL

More than 99% achievable in 1ms

Probable limitation: laser light polarization

Experience from COLLAPS

Examples!

^{31}Mg: G. Neyens et al, PRL 94, 022501 (2005)

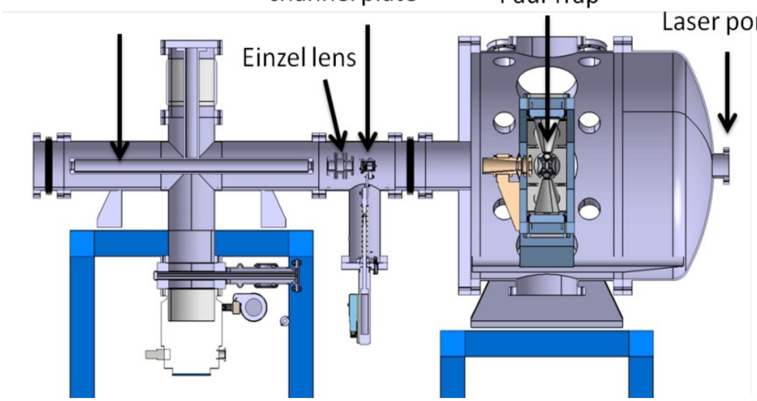
$^{21-32}$Mg: D. T. Yordanov et al, PRL 108, 042504 (2012)

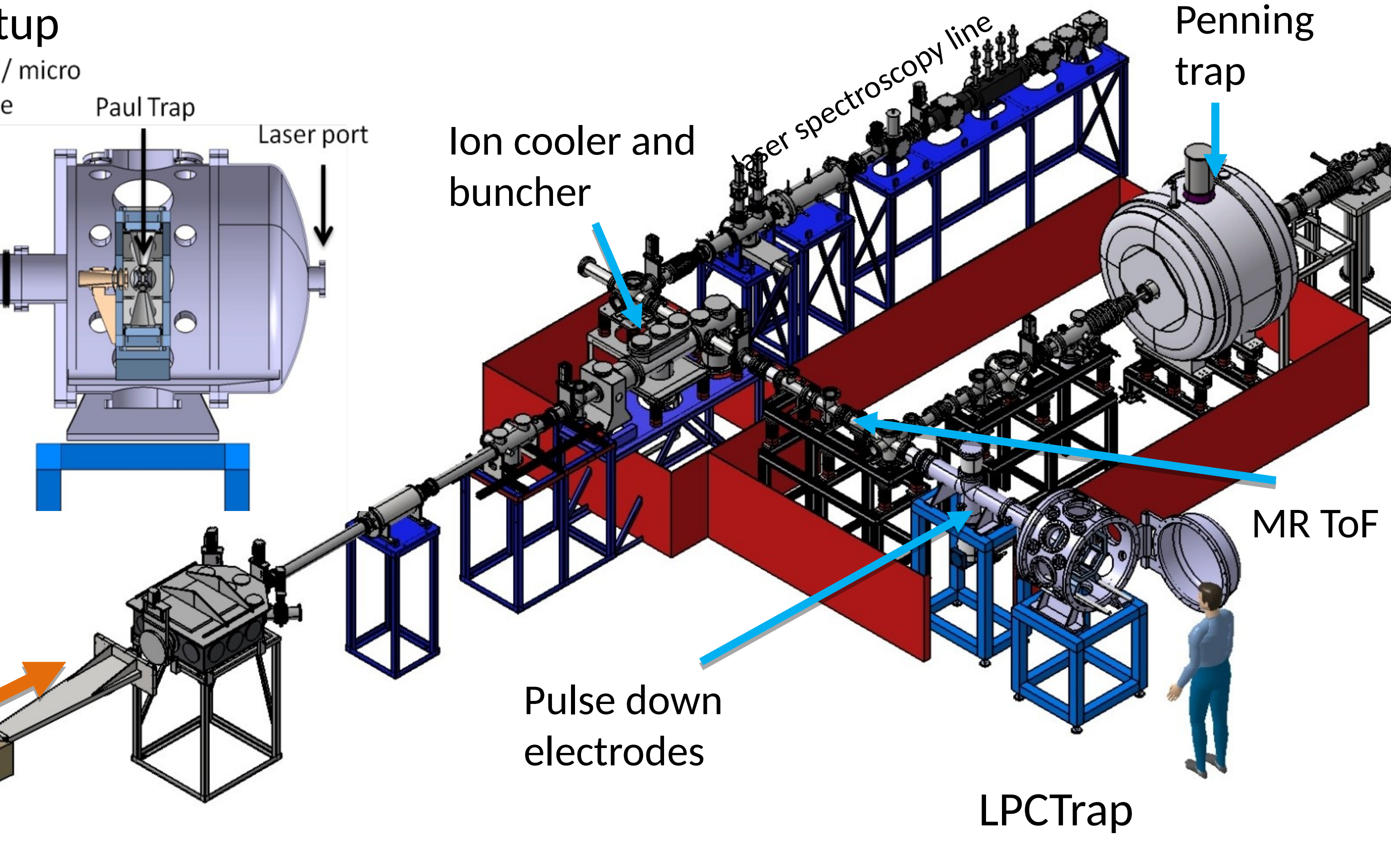
Proof of principle in JYFL

1) Laser polarization 2) First *D* measurement

2018-2021

LPCTrap setup





IGISOL – 4 : I. D. Moore et al., Nucl. Instrum. Meth. B, 317(2013)208

IGISOL: ~ 10^5 pps of ^{23}Mg

D measurement at GANIL-SPIRAL

THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY

Low Energy Beams :

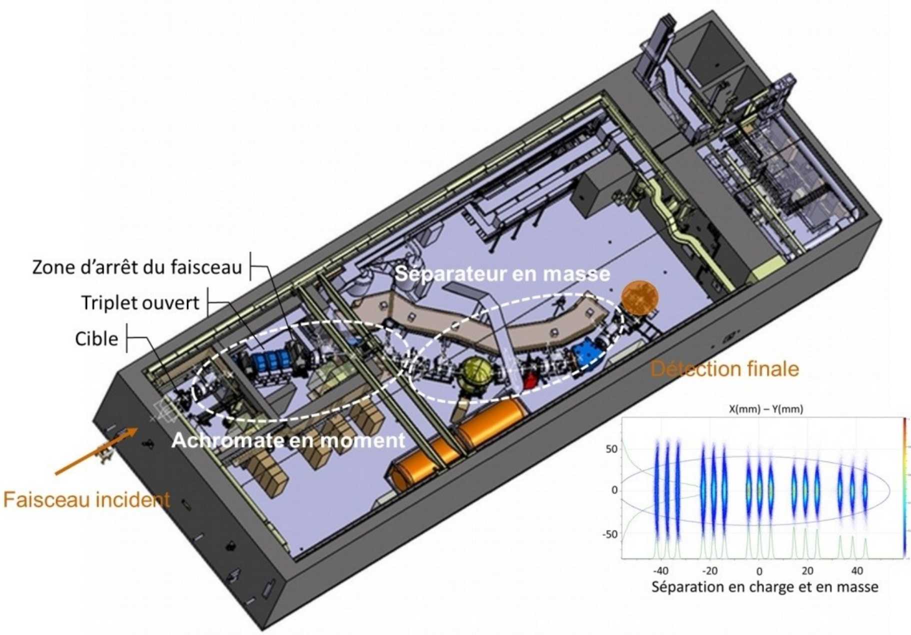
2022-...

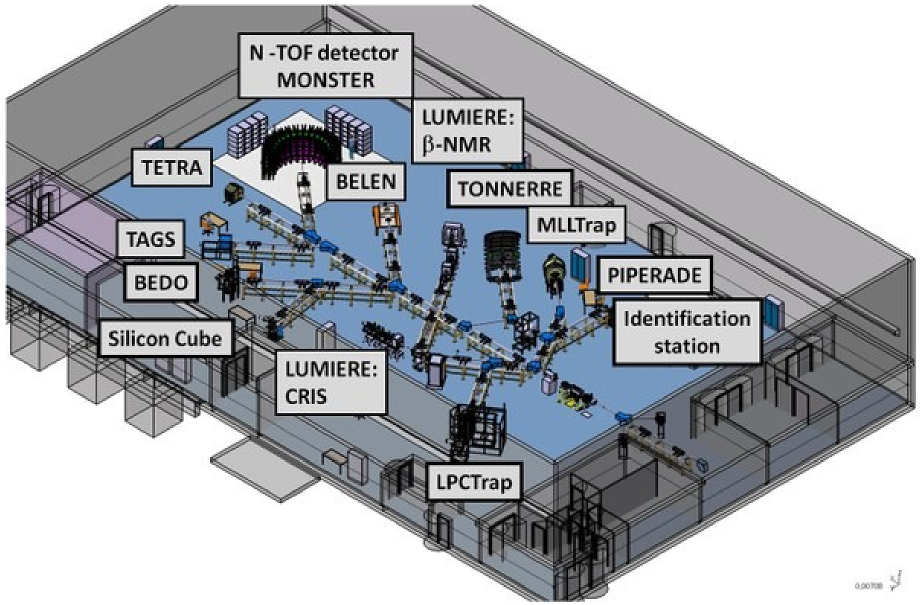
S3 LEB

Traps and laser setups

DESIR

Ground state properties and β-decay of exotic nuclei





Beams from fusion evaporation using the SPIRAL 2 LINAC

Gas cell technique: interesting perspectives for ^{39}Ca: up to 10^7 pps

Beams from S3 – LEB and SPIRAL / GANIL

SPIRAL 1: highest yields for ^{23}Mg > 10^8 pps

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Status: preparing venue at JYFL

- MORA setup development
  - Trap, RF, mechanical supports and chambers under development
  - Phoswhich detectors for β detection under tests
  - MCP + positioning anodes being purchased
- Implantation of MORA at JYFL
  - Available lasers:
    - pulsed (TiSa) - ok
    - CW (Dye) as alternative option: not available yet
  - Beam purification in the IGISOL 4 lines
    - MR ToF MS is being developed
      - Important for suppressing the ^{23}Na contamination
- Production test at JYFL: October 11th -15th
  - Comparing ^{23}Na background as a function of ^{23}Mg beam intensity for:
    - ^{23}Na(p,n)
    - ^{24}Mg(p,d)
  - Results:
    - >10^5 pps of ^{23}Mg for both reactions - ok
    - ^{23}Na:^{23}Mg from 200-1000:1 for ^{24}Mg(p,d) , contamination too large for ^{23}Na(p,n)
    - – to be reduced by a factor of 10 by eg mass separation in MR ToF MS and Penning trap, and/or using clean pieces for the IGISOL gas cell

Summary/Perspectives

- New perspectives with polarized beams with MORA at JYFL
  - Proof of principle of the polarization to be done at JYFL
    - Adapted IGISOL – 4 Laser setup
      - Pulsed (TiSa) or CW (Dye) laser schemes are being investigated
    - Adapted trapping setup from LPCTrap
    - Adapted detection setup carried out by GANIL and LPC Caen

2018-2020

  - First measurement of *D* at JYFL
    - Best sensitivity for nuclear beta decay is probably possible
      - Test run for ^{23}Mg beam characterization

2020-2021

- *D* correlation measurement with unprecedented accuracy in SPIRAL 2
  - 1 week of beam time:
    - same accuracy as for the neutron with existing techniques
    - Better sensitivity to NP: type of transition and selection of detection plane
  - Can go down to the 10^{-5} level with some beam, laser and trapping R&D
    - improvement by 1 order of magnitude on the sensitivity to NP $Im(C_V/C_A)$
    - First approach /probe of D_{FSI} for ^{23}Mg
  - Great physics with great challenges!
- Project has officially started this year

2022-…

Thanks a lot for your attention

THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY

lpc caen — laboratoire de physique corpusculaire

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JYFL

I. Moore
T. Eronen
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A. Kankainen
S. Rinta - Antila

KU LEUVEN
NUCLEAR AND RADIATION PHYSICS

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The University of Manchester

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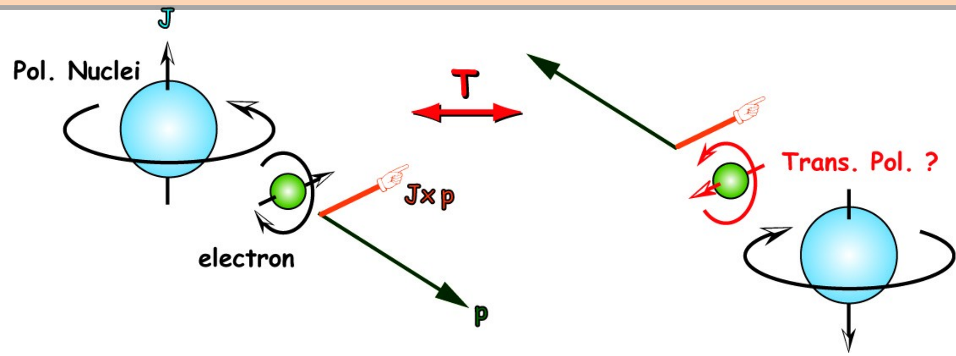
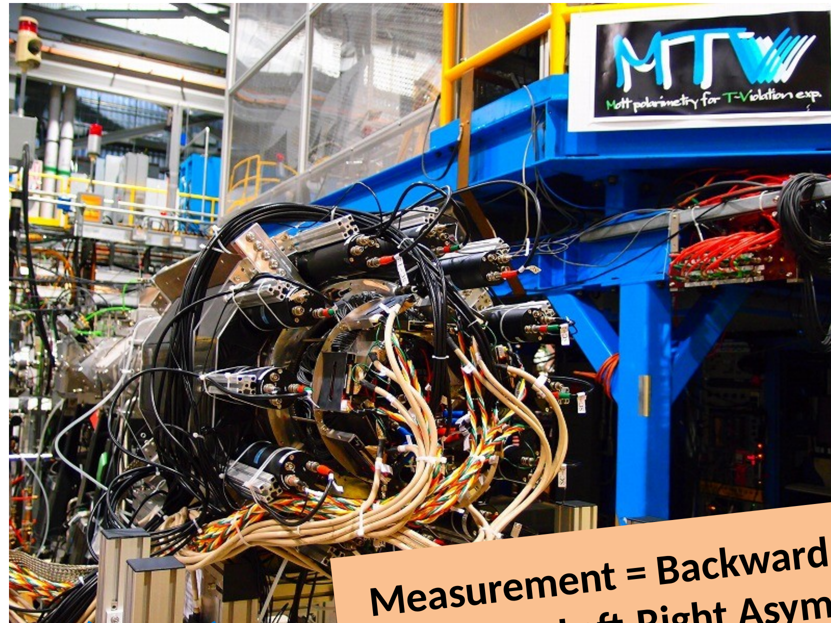
RÉGION NORMANDIE

S1183-MTV : Test of time reversal symmetry using polarized unstable nuclei

Collaboration between Canada-Japan (Spokesperson : Jiro Murata, Rikkyo University, Japan)

Motivation : Searching T-Violating Transverse Electron Polarization in polarized Li-8 beta decay
T & P violating (same as EDM, but in different system)





Measurement = Backward Mott Scattering Left-Right Asymmetry

RIUMF (Canada)

MTV detector (Japan)

Polarized Li-8 : TRIUMF-ISAC

10^7pps @ 80% polarization

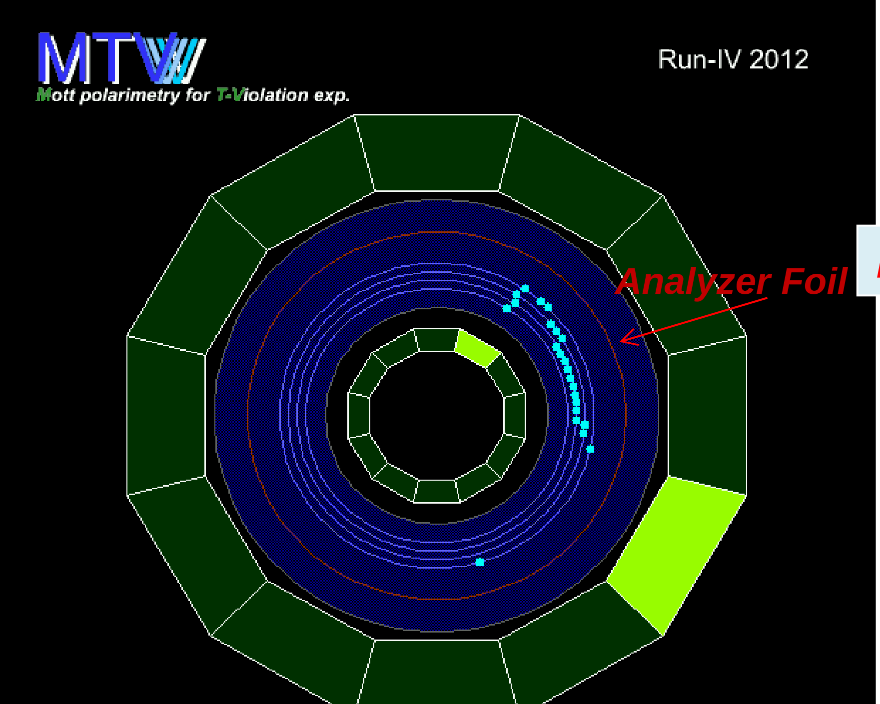
+

Transverse Electron Polarimeter :
Mott Analyzer using Cylindrical Drift Chamber

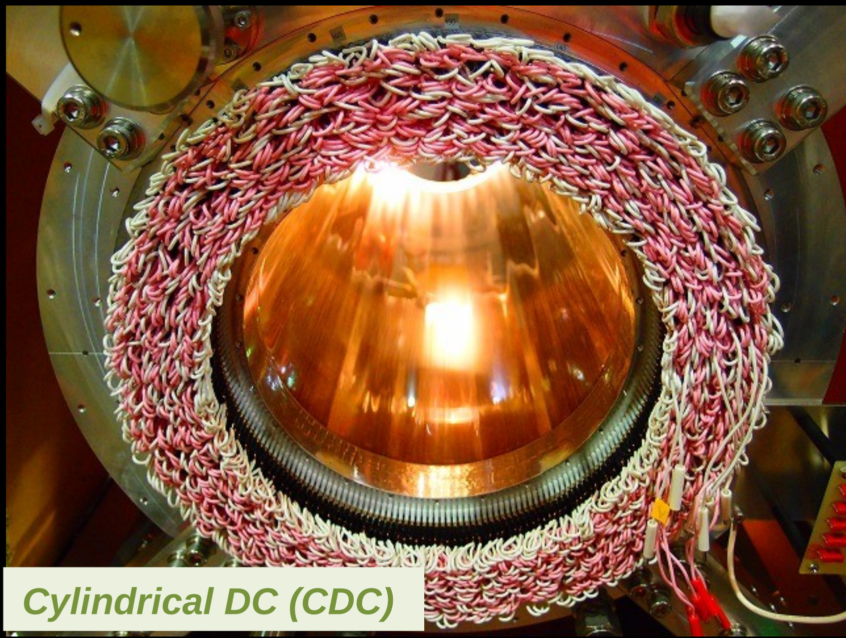
50MHz Mott-Scattering Tracking Measurement

Highest Precision Test at *R* ~ 10^{-4}

Previous Test at PSI 2003 $R_{PSI} = (-0.9 \pm 2.2) \times 10^{-3}$ ***the only project testing R***



Scattering Event



Cylindrical DC (CDC)

KEK

2008 Test Experiment at KEK-TRIAC

R~40% with 8% pol., 10^5pps

KEK to TRIUMF

TRIUMF

2011 – 2012 CDC Commissioning
2013 – 2015 Systematics Tests
2016 – 2017 Physics Production

Data Production Completed with ~10^{-4} precision!

Physics from Run 2016-17 (preliminary)

1. Test of *R* at the highest precision.
2. First measurement of nuclear *N correlation* *(transverse polarization)*.
3. Lorentz violation tests in weak interaction *(half-life varying of pol. Li-8)*.

MTV Collaboration

Japan : Rikkyo-U, Tohoku-U, Nagoya-U, RIKEN
Canada : TRIUMF

E_1 coefficient: five-fold correlation

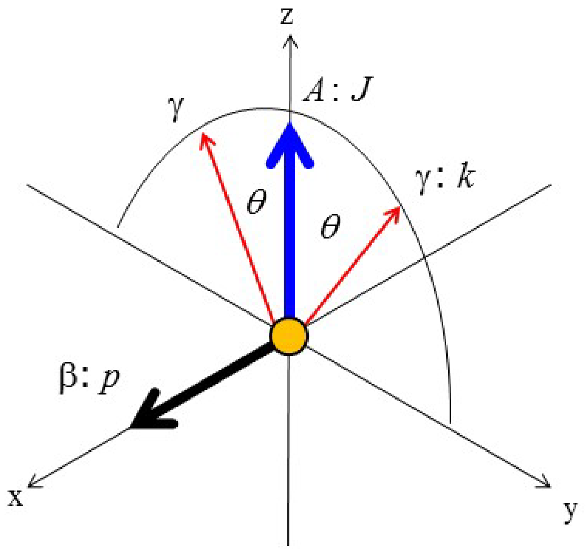
$$W_{\beta-\gamma} \propto 1 - AE_1 \left(\boldsymbol{J} \cdot \boldsymbol{p} \times \boldsymbol{k} \right) \left(\boldsymbol{J} \cdot \boldsymbol{k} \right)$$

"nuclear tensor polarization"-β-γ directional correlation

$$E_1 \propto M_F M_{GT} \Big[\mathrm{Im} \left(C_V C_A'^* + C_V' C_A^* - C_S C_T'^* - C_S' C_T^* \right)$$
$$\pm \frac{\alpha Z}{p} \mathrm{Re} \left(C_S C_A'^* + C_S' C_A^* - C_V C_T'^* - C_V' C_T^* \right) \Big]$$

T : odd
P : odd

$$\approx \frac{2y \sin \varphi}{1 + y^2} \qquad y e^{i\varphi} \equiv {}^{C_A M_A}/_{C_V M_V}$$



$$AE_1 (J \cdot p \times k) \rightarrow AE_1 \sin\theta \cos\theta$$

M. Morita and R. S. Morita, PR107, 1316 (1958); R. B. Curtis and R. R. Lewis, PR107, 1381 (1958);
B. R. Holstein, PRC5,1529 (1972).

K. Minamisono, O. Naviliat-Cuncic

E_1 Recoil order terms

$$E_1 = \frac{1}{|a|^2+|c|^2}\delta_{JJ'}\frac{3J}{4\sqrt{J(J+1)}(2J+3)}2\,\mathrm{Im}\,a^*\left[c-\frac{E_0}{3M}(c\pm b\pm d)+\frac{E}{3M}(7c\pm b\pm d)\right]$$

$$\sim\frac{2\,\mathrm{Im}\,a^*c}{|a|^2+|c|^2}=\frac{2y\sin\varphi}{1+y^2}$$

$$E_1^{EM}=\frac{1}{|a|^2+|c|^2}\left[\mp\frac{Z\alpha E^2}{4Mp}2\,\mathrm{Re}\,a^*\left\{c\mp b\pm d-\frac{m_e^2}{E^2}(3c\mp b\mp d)\right\}\right]$$: final state interaction

$E_1 = (-110 \pm 220)\times 10^{-4}$: ^{58}Co :F. P. Calaprice et al., PRC15,381(1977)

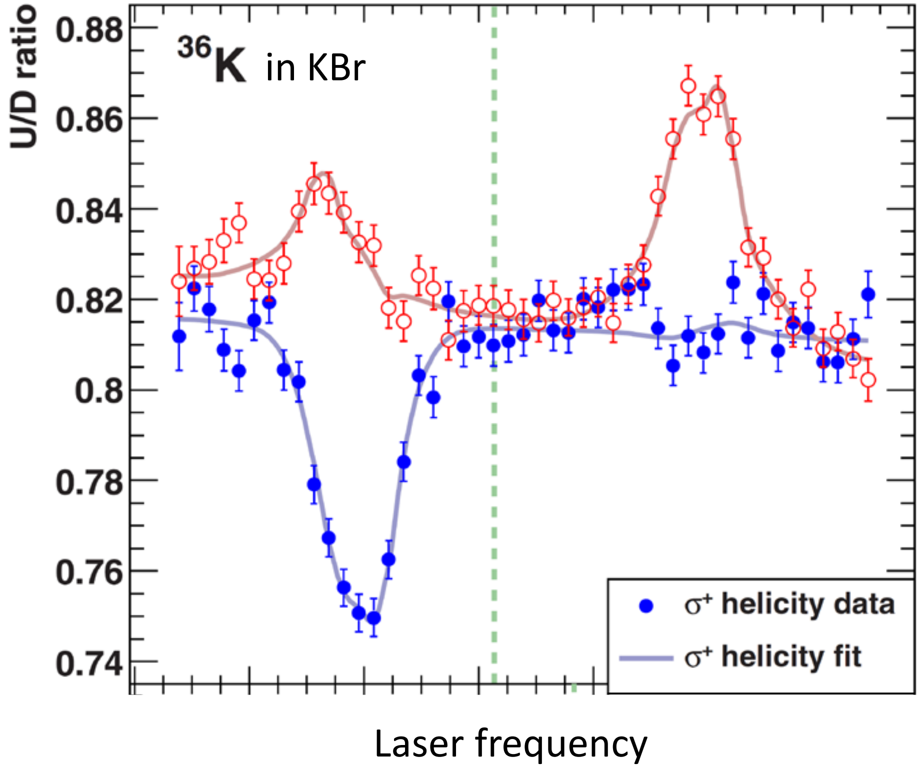
$E_1 = (-10 \pm 60)\times 10^{-4}$: ^{58}Co :J. L. Mortara, PhD thesis, UCB (1999)

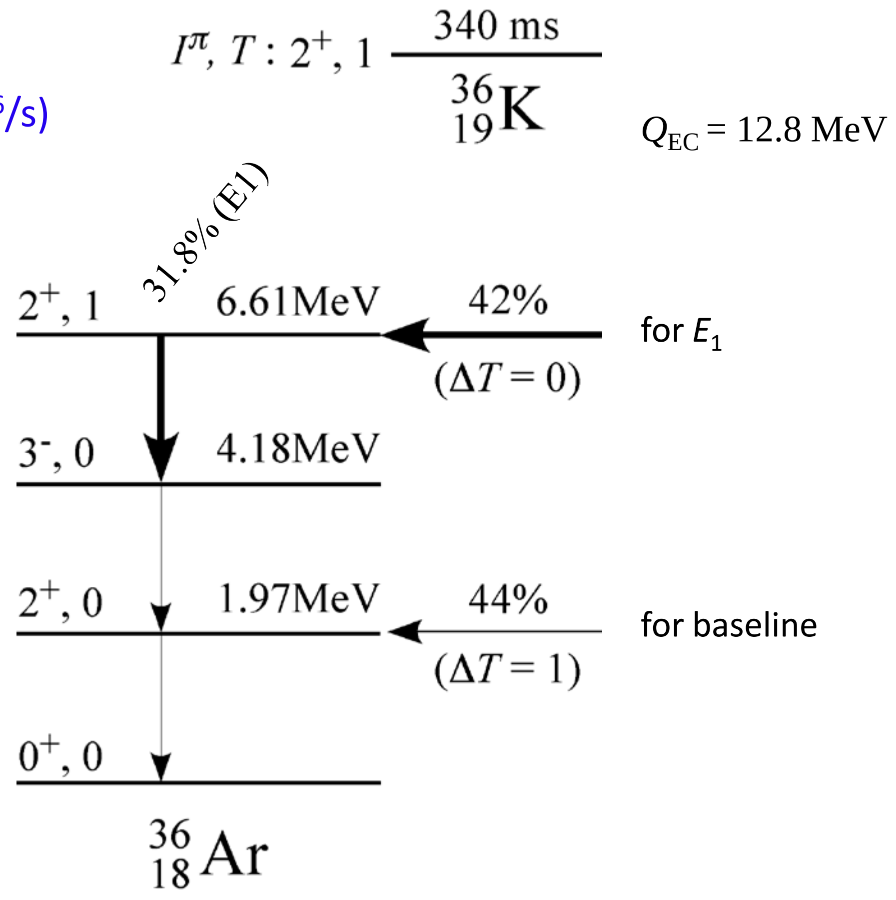
- Order of magnitude larger error bar than *D* or *R*: need more precise measurements
- ^{58}Co GT transition dominated by C_A: not sensitive to E_1
- need measurement in other systems

B. R. Holstein, PRC5,1529 (1972).

A-β-γ correlation in ^{36}K

- Polarized ^{36}K beam available at BECOLA at NSCL/MSU with optical pumping
- Current rate at NSCL: ~ 10^3/s (stopped beam at BEOCLA)
- AP ~ -5% (A not known, $|P|$ > 15%)
- To be competitive with D & R, need beam from FRIB & cyclotron stopper (>10^6/s)
- Larger P possible with optimized laser system





A. R. Young et al., PRC52, R464 (1995); D. M. Rossi et al, PRC92, 014305 (2015).

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