Measurement of the β-ν angular correlation in the decay of trapped $^6He^+$ ions

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Using β decay to probe the weak interaction

Generalization of Fermi's original theory of β decay:

→ 5 interactions : *i* = *V,A,S,T,* and *P*

Strengths C_i , C_i' are free parameters of theory!

Using β decay to probe the weak interaction

Motivations

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Determination of relative strengths of interactions:

→ β–ν angular correlation coefficient a

- Gamow-Teller transitions
  (*A* and *T* can be effective)

$$a_{GT} = \frac{1}{3}\frac{|C_T|^2 + |C_T'|^2 - |C_A|^2 - |C_A'|^2}{|C_T|^2 + |C_T'|^2 + |C_A|^2 + |C_A'|^2}$$

- Fermi transitions
  (*V* and *S* can be effective)

$$a_F = \frac{|C_V|^2 + |C_V'|^2 - |C_S|^2 - |C_S'|^2}{|C_V|^2 + |C_V'|^2 + |C_S|^2 + |C_S'|^2}$$

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SM (V-A theory):

$C_i = -C_i'$ *real*
$C_S = 0$
$C_T = 0$

$\Rightarrow$ $a_{GT} = -1/3$, $a_F = 1$

Present constraints (95.5%CL):

$|C_T / C_A| < 0.08$

$|C_S / C_V| < 0.07$

(right handed *S* & *T*)

Severijns et al. *Rev.Mod.Phys.* ***78*** *991 (2006)*

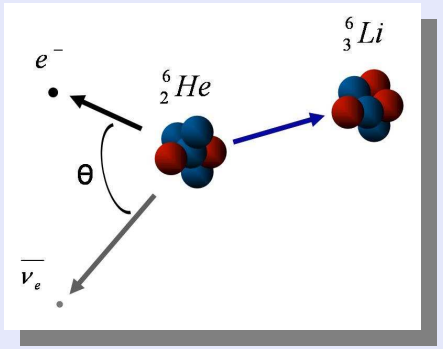
How true ? $C_S \neq 0$? $C_T \neq 0$?

Coefficient a measurement

Allowed transitions, unpolarized nuclei :

$$N(E_e,\theta)dE_e d\theta = N_0\,(\,1 + a\,\frac{V_e}{c}\cos(\theta) + \frac{m_e}{E_e}b\,)\,dE_e d\theta$$

- The β-ν relative angle θ cannot be measured directly…
- a is inferred from the recoil ion (RI) energy spectrum



Coefficient a measurement

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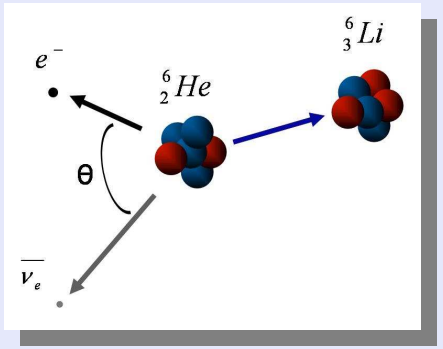

Most precise measurements of a_F :

$a_F = 0.9989 \pm 0.65\%$	^{32}Ar	γ Doppler shift	*Adelberger et al. (1999)*
$a_F = 0.9981 \pm 0.48\%$	$^{38}K^m$	Magneto-Optical Trap β - RI coincidence	*Gorelov et al. (2005)*

Most precise measurements of a_{GT} :

~ 50 years old!!!

$a_{GT} = -0.3308 \pm 0.9\%$	^6He	RI energy	*Johnson et al. (1963)*
$a_{GT} = -0.3190 \pm 8.8\%$	^6He	β - RI coincidence	*Vise and Rustad (1963)*

Only one measurement at the level of 1% precision for GT
Need for new measurements

Trapping ^{6}He

goal for LPCTrap:

- Improve precision on a_{GT} *(~0.5%)*
- Coincidence measurement
  (E_{RI},E_{β},$\theta_{RI-\beta}$→ better control of systematics)
- Trapped radioactive nuclei
  (matter free environment →reduce scattering)

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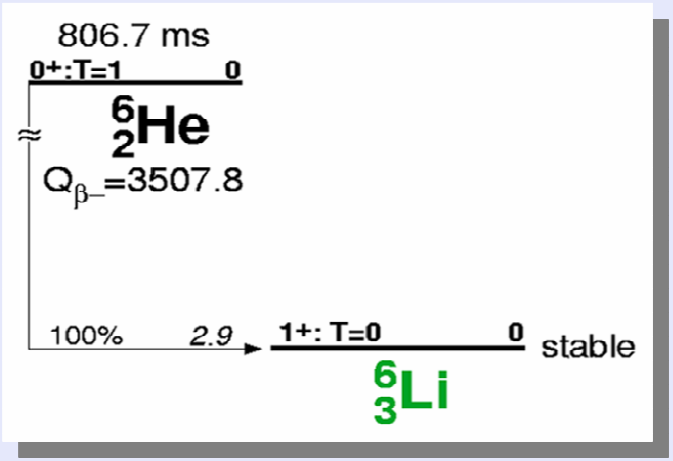
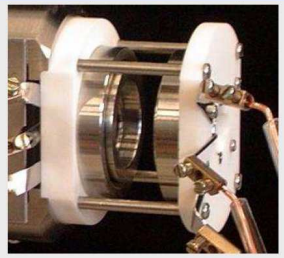
Good candidate for a_{GT}: ^{6}He

- Pure Gamow-Teller ($\Delta J = +1$)
- 100% G.S to G.S.
- Reasonable Half life = 0.8 s
- High Q_β=3.51 MeV → E_{RI} <1.4 keV
- Sufficient production @ GANIL



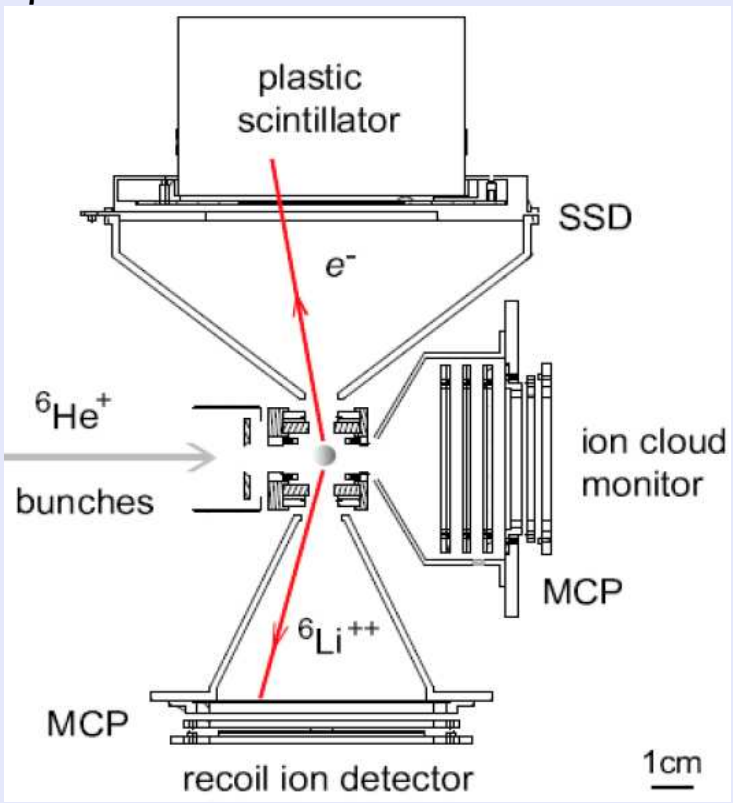
Principle of the measurement

- Decay source: $^6He^+$ ions confined in a transparent Paul Trap
  (works for any singly charged ions)

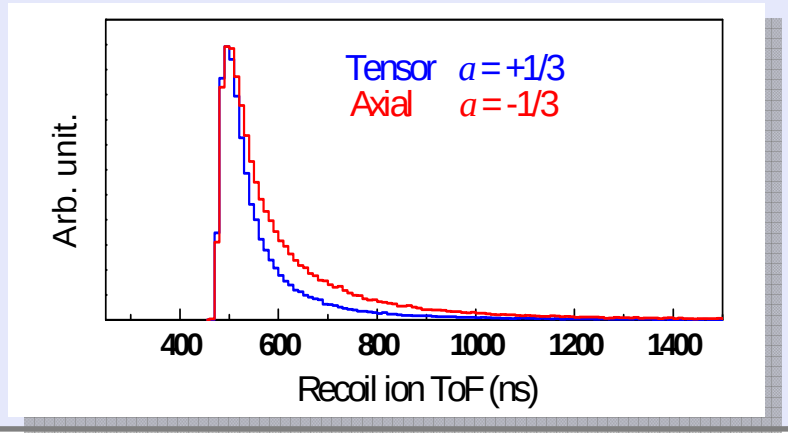


P. Delahaye's PhD

- β and RI detected in coincidence

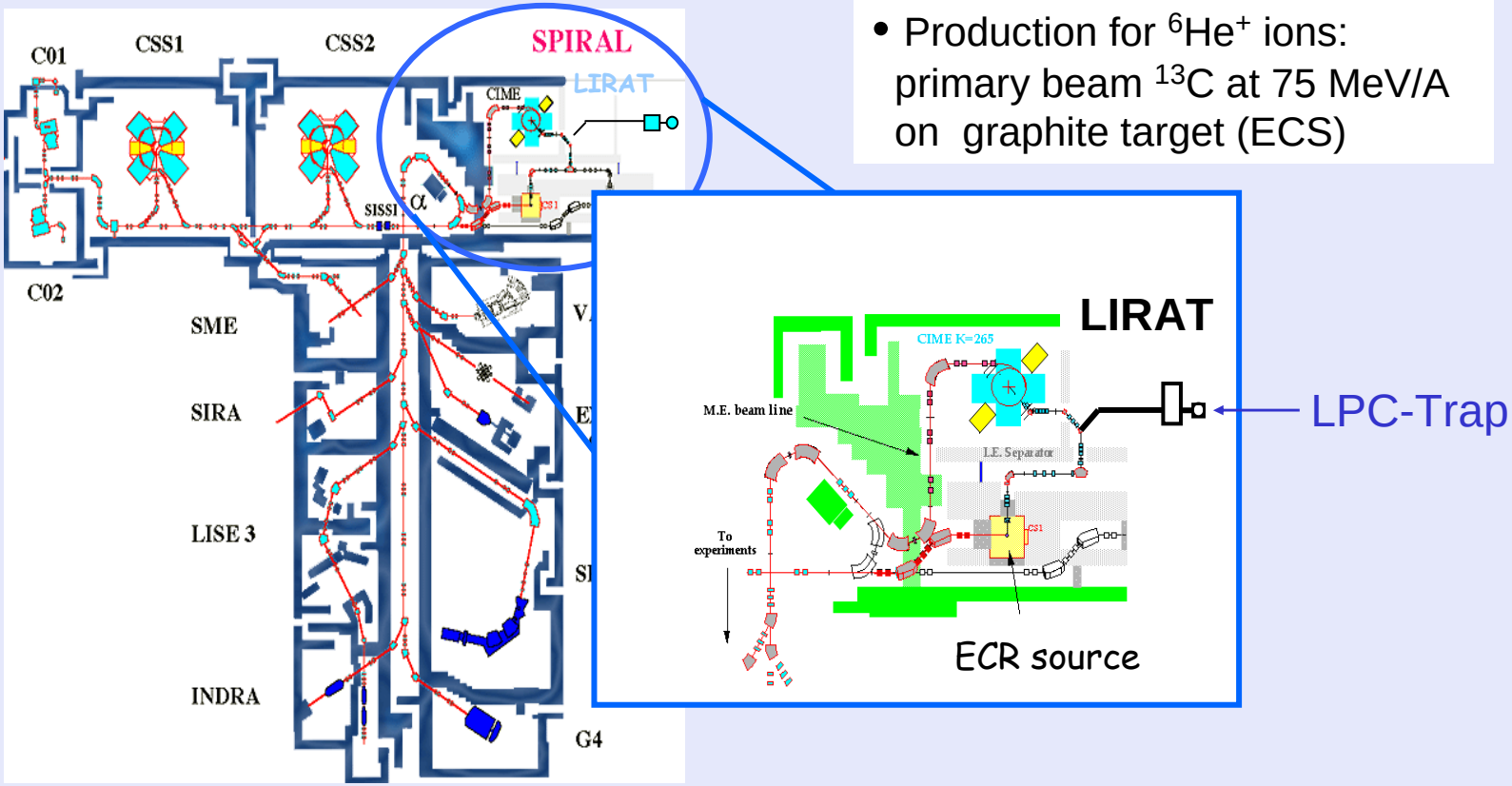


- Recoil ion ToF spectrum (sensitive to a_{GT})



- 3 observables E_β , E_{RI} , $\theta_{\beta\text{-RI}}$
  - → Background rejection
  - → Systematic effects investigation

Ion production at GANIL

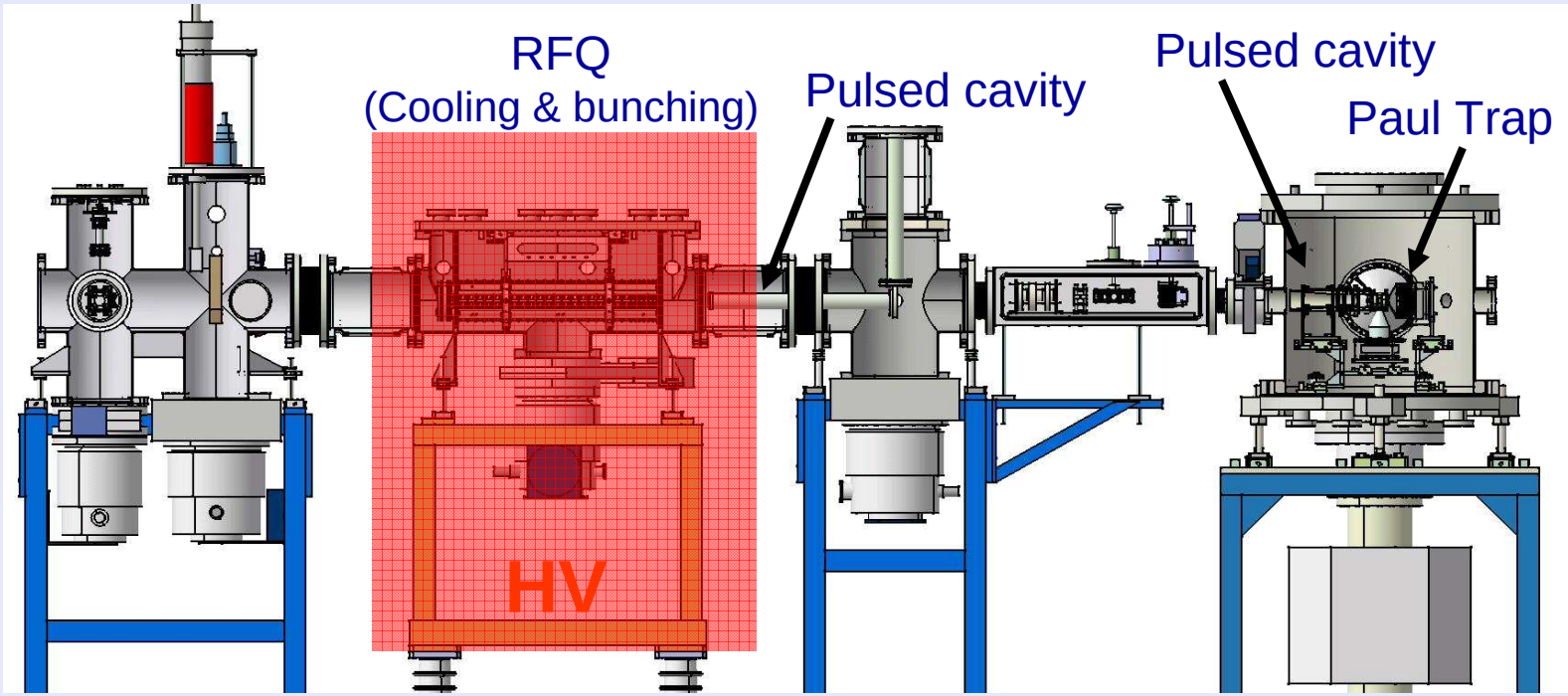


- Production for $^{6}He^{+}$ ions: primary beam ^{13}C at 75 MeV/A on graphite target (ECS)

- Continuous $^{6}He^{+}$ beam from SPIRAL ECR ~10^{8} pps, E=10 keV, ΔE~20 eV, 80π mm mrad

Trap requires cold, and low energy ion bunches !

Beam preparation

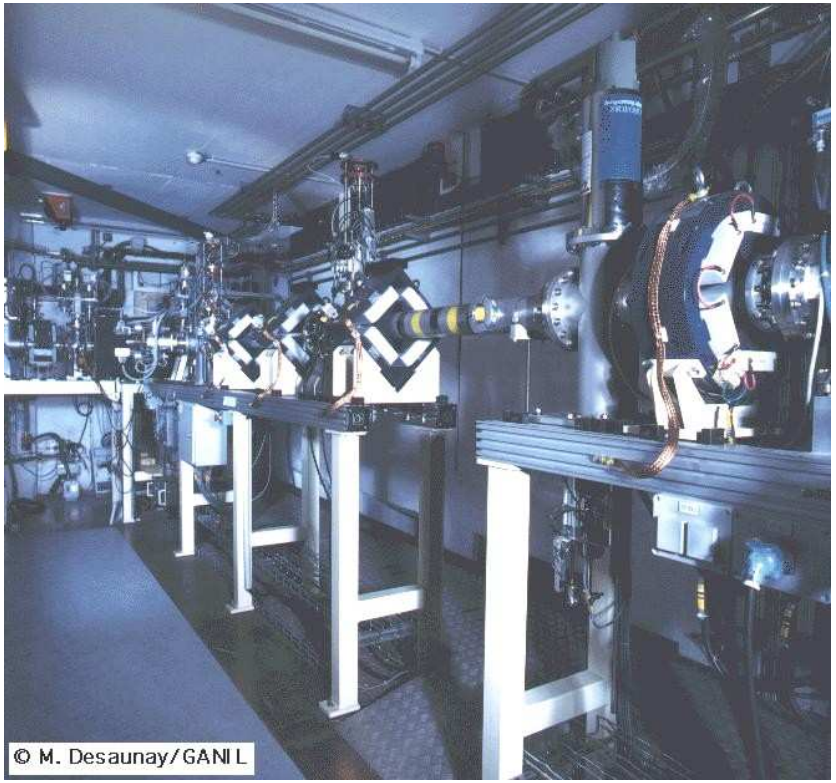


KE_{ion}:	10 keV	100 eV - <1 eV	1 keV	100 eV 0 eV
ΔKE:	~20 eV	~1 eV		~0.1 eV

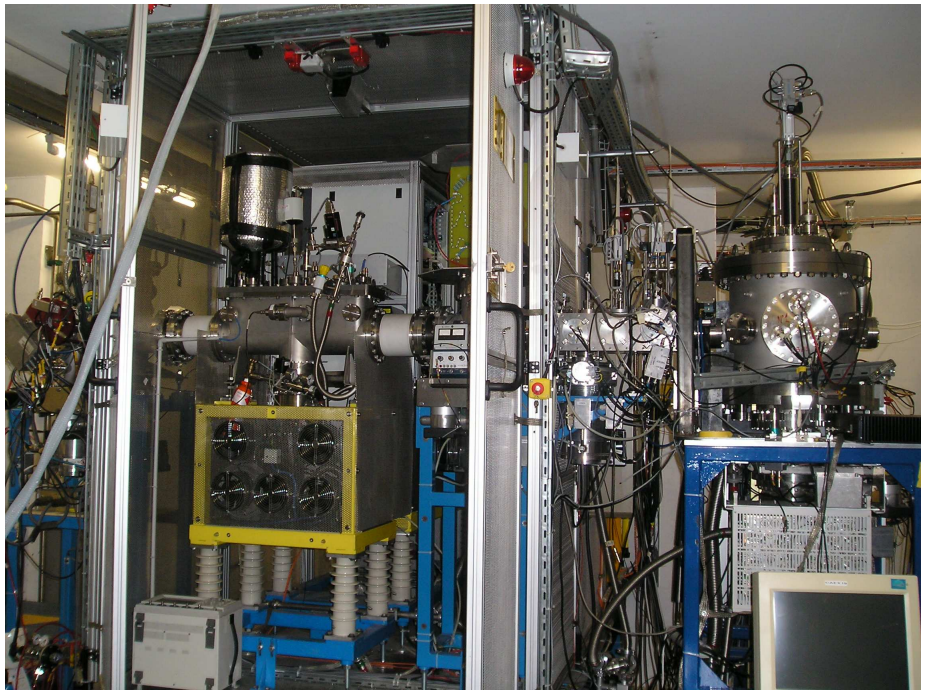
Efficiency: ε ~ 1-1.5% @ T_{duty} = 200ms ε ~ 40% ε ~ 20%

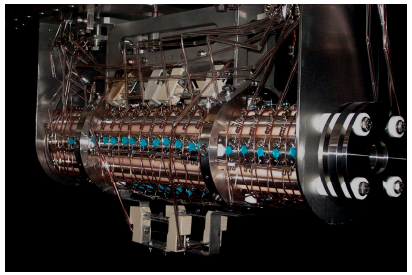
D.Rodriguez et al. *NIMA565(2006)*

Pictures

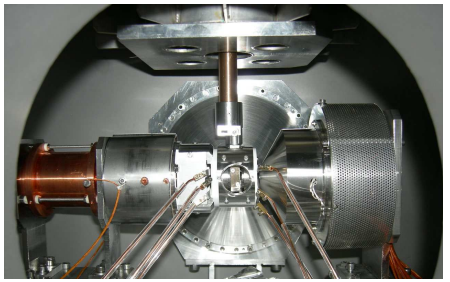


LIRAT beam line





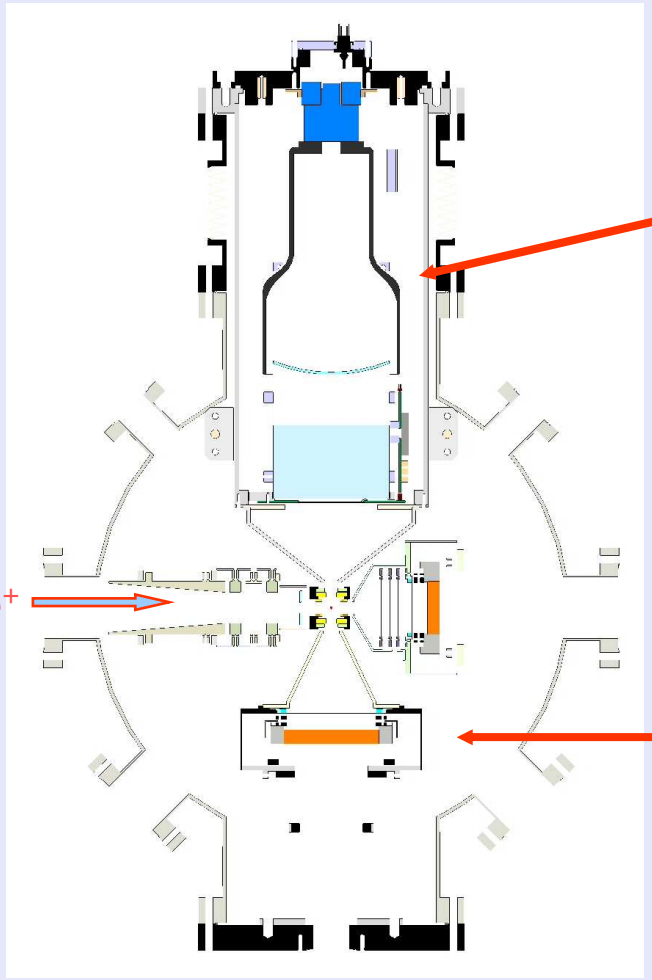
RFQ



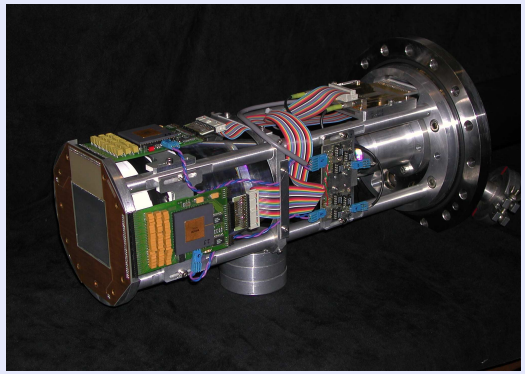
Paul Trap

The β decay detection setup

Detection chamber

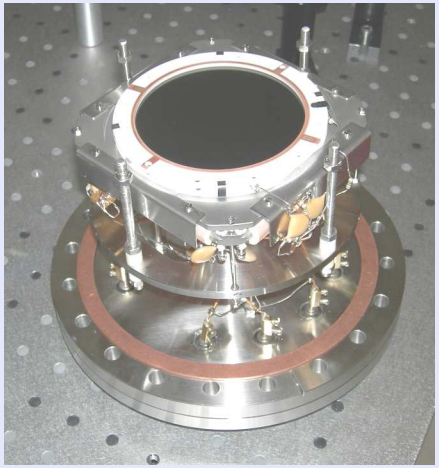


β telescope



- DSS Silicon Detector
  - 60 x 60 mm x 300 μm
  - 1 mm spatial resolution
- Plastic scintillator
  - σ_E 10 % at 1 MeV
  - σ_T ~ 200 ps

MCP detector

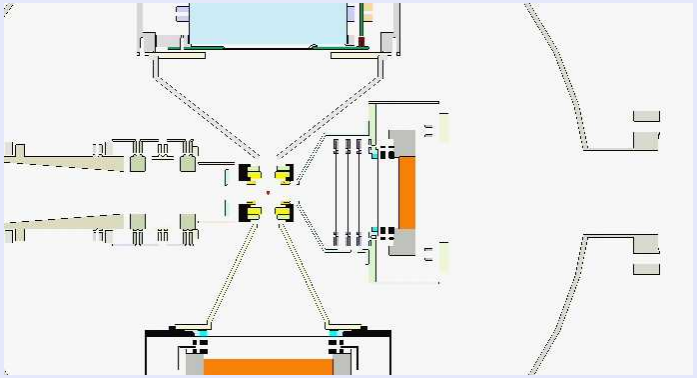


- MCP
  - Active Ø 800 mm
  - σ_T ~ 200 ps
- Delay lines
  - σ_x,σ_y ~ 200 μm

E. Liénard et al.
NIMA 551,375 (2005)

Typical ion cloud characteristics

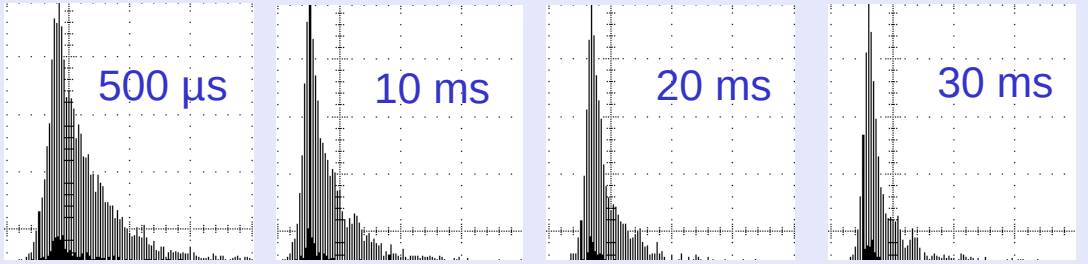
Using the MCP ion cloud monitor downstream:



- *Ion counting*
- *Tof distributions of extracted ions (200 ns/div)*

→

- *Temperature*
- *Size*



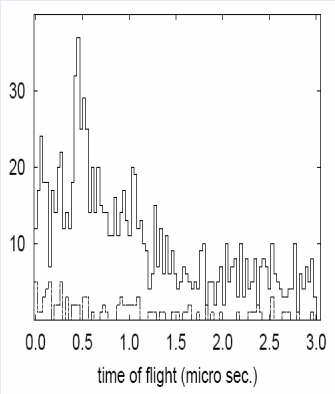
Evidence for further in trap cooling
(only $2x10^{-6}$ mbar H_2 buffer gas)

Typical characteristics:

- Ion cloud size : ~5 → ~2 mm
- Temperature : ~1 eV → ~0.1 eV
- Capacity : Up to ~2 10^5 trapped ions
- Trapping time : 200 – 500 ms

LPC-Trap experiment status

- 2005 : Commissioning run at GANIL with $^6He^+$
  → ~500 coincidences in 6 hours
  - proof of principle for the experiment (first in-trap decay measurements with a Paul trap)



- 2006 : 1 week of beam time
  → ~700 ions permanently trapped and 10^5 "good events" recorded
  - a_{GT} with ~2% relative uncertainty (statistical)
  - start a careful study of systematic effects
  - need to improve the setup efficiency

Fléchard et al.
PRL 101, 212504 (2008)

- 2008 : 1 week of beam time (efficiency improved by factor 20)
  → 4 x 10^6 "good events" recorded
  - a_{GT} with ~0.3 % statistical relative uncertainty!!!

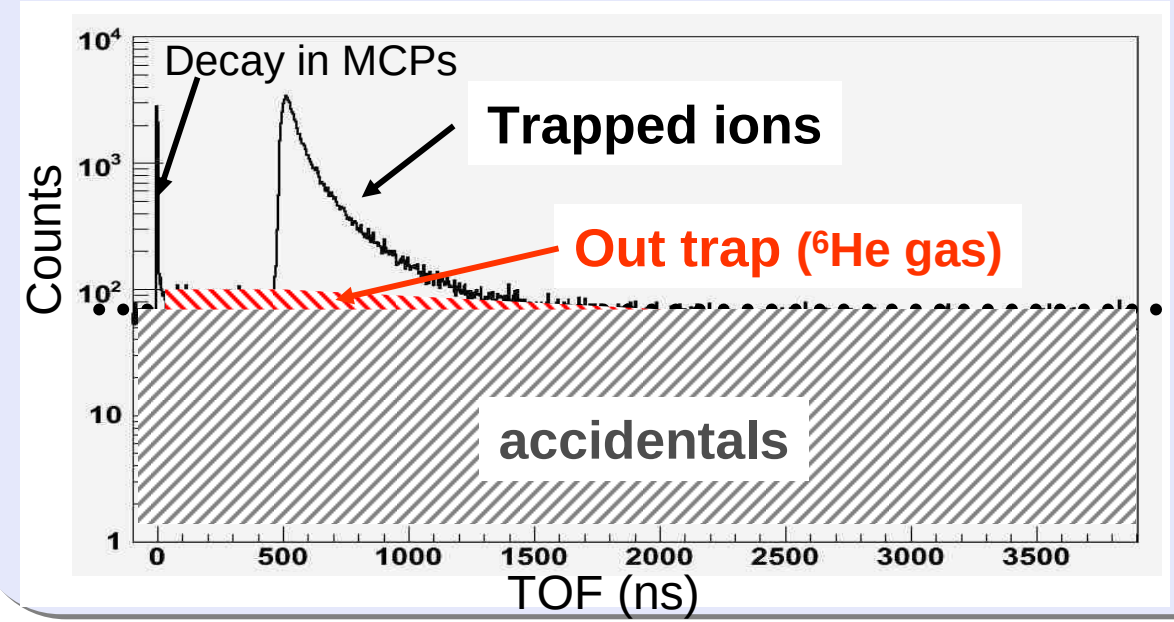
Potential for new physics!

P. Velten's PhD

Data analysis

2006 experiment

Key observable: Experimental TOF spectrum



~10^5 experimental Good events

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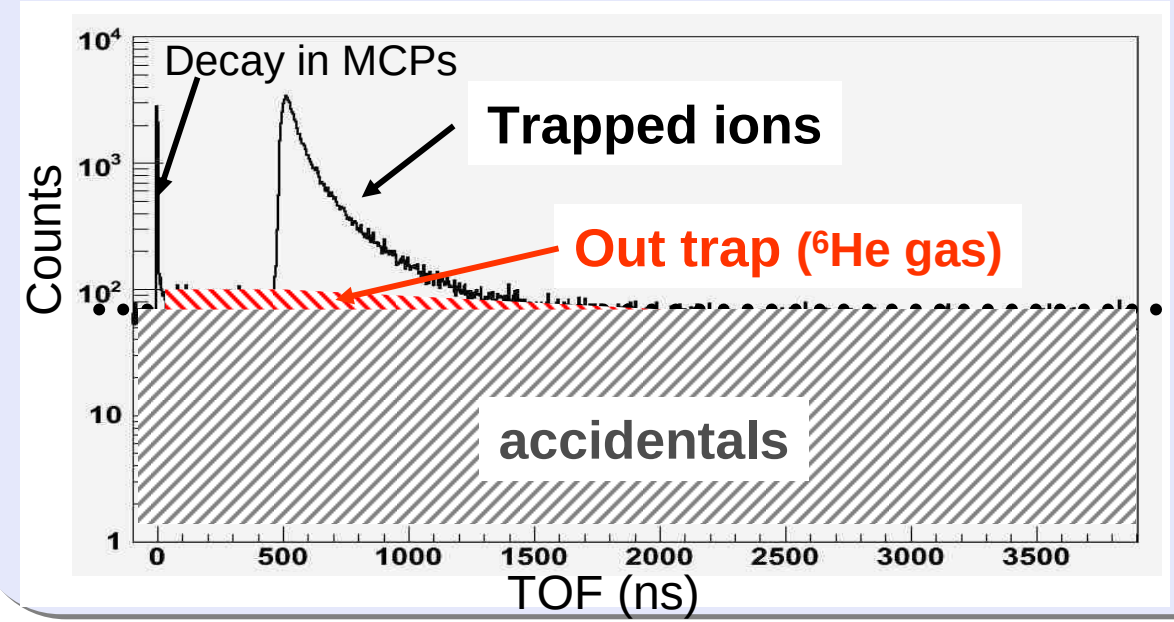


~10^5 experimental Good events

sets of background MC simulated events

- *accidentals (a = -1/3)*
- *out-trap decays (a = -1/3)*
- *events with scattered β (a = -1/3)*

2 sets of ~5 x 10^5 MC simulated events

- *Axial in-trap decays (a = -1/3)*
- *Tensor in-trap decays (a= + 1/3)*

TOF_{exp} *(corrected)*

TOF_A
TOF_T

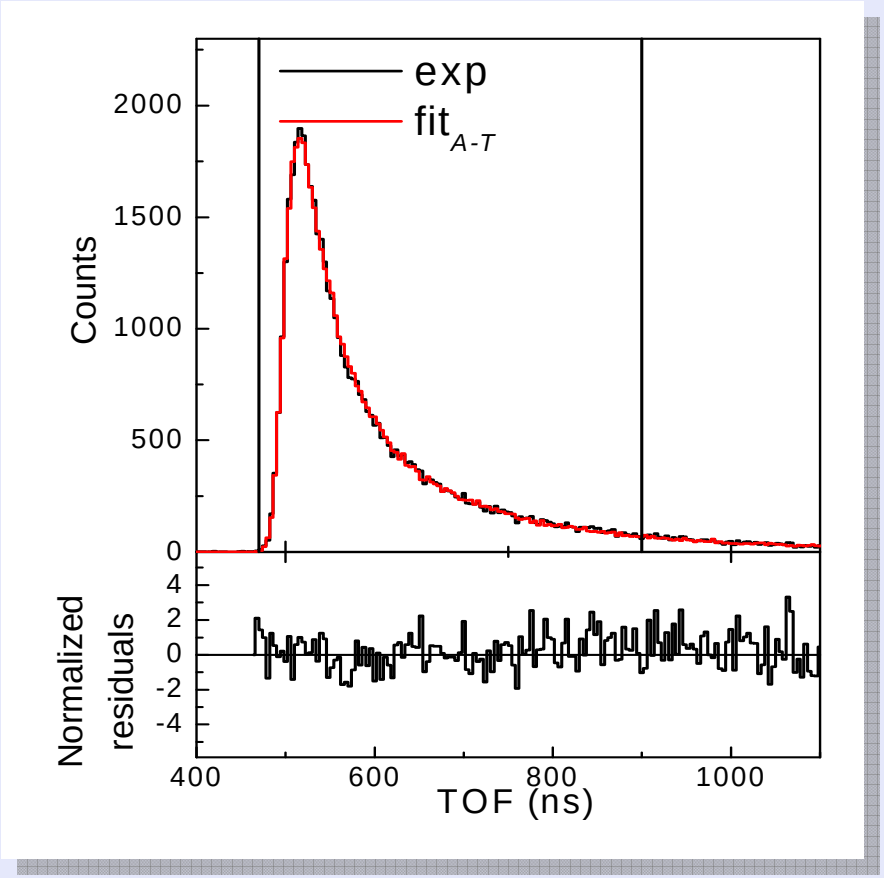
TOF_{exp} fit function:

$$f = \alpha \times TOF_A + \beta \times TOF_T$$

$$a_{exp} = -1/3\ \alpha + 1/3\ \beta$$

Data analysis

2006 experiment



Statistical error

a_{exp} = - 0.334 ± 0.007 (stat)

(~2% relative uncertainty)

Goodness-of fit

χ^2 / ndf = 0.915
(ndf = 106)

P-value = 0.72

Systematic error ???

Data analysis

2006 experiment

Difficulty: MC simulation ingredients…

- Background events generation and normalization
- Backscattering of the β particles
- Ion cloud size and temperature
- RI propagation in the Trap RF field
- Position, orientation, efficiency, and resolution of the detectors
- Li^{3+} / Li^{2+} ratio (ionization by shake-off)
- …

Most part of the analysis work :

1) determination of MC simulation parameters
(using the experimental data, independent measurements, or calculations)
& estimation of their contribution to the systematic error on a_{GT}

2) check of the simulation reliability using all available observables

Systematic errors

2006 experiment

Error source	parameter determination	Δa_{GT} (x 10^{-3})	
Cloud size (T°)	exp. data + indep. measur.	± 5.4	*Proportional to statistical error*
RI detector location	exp. data	± 4.2	
RI detector calibration	exp. data	± 1.3	
β detector location	exp. data	± 0.3	
β detector calibration	exp. data+indep. measur.	± 1.1	
Background	exp. data	± 0. 9	
β back scattering	geant4 (±10%)	± 1.9	
Li^{2+} shake-off	0-0.05	± 0.6	
Trap RF field effect	2.5%	± 1.7	

$$a_{GT} = -0.334 \pm 0.007_{(stat)} \pm 0.008_{(syst)}$$

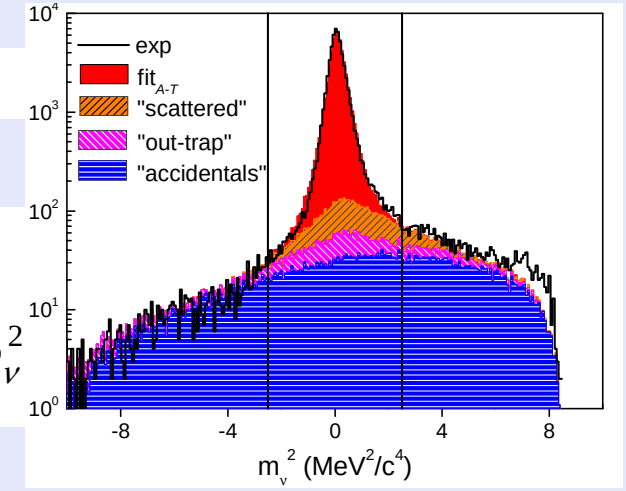
Simulation reliability (examples)

2006 experiment

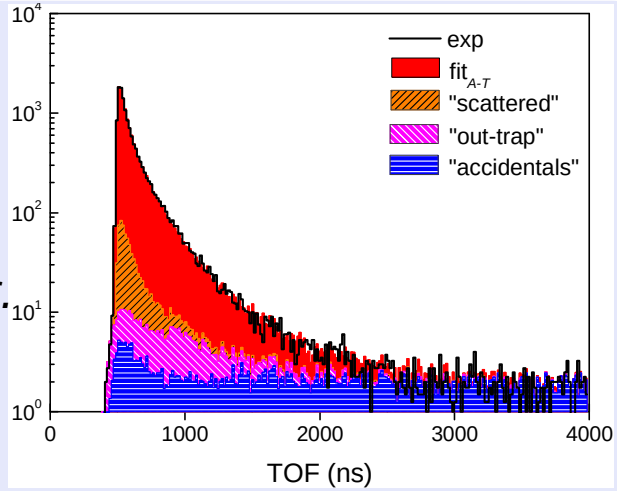
E_β , E_{RI} , $\theta_{\beta\text{-}RI}$

Neutrino mass reconstruction

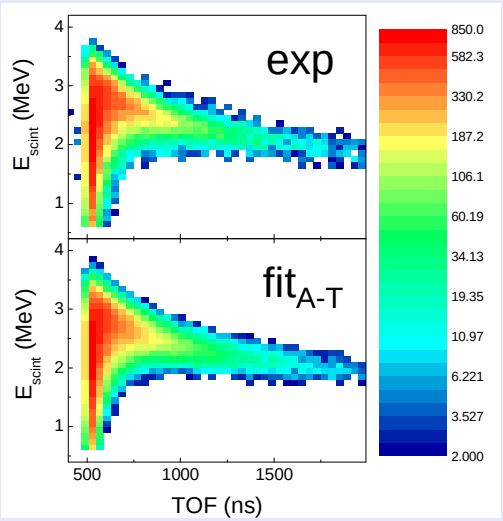
$$M_\nu^2 = E_\nu^2 - p_\nu^2$$



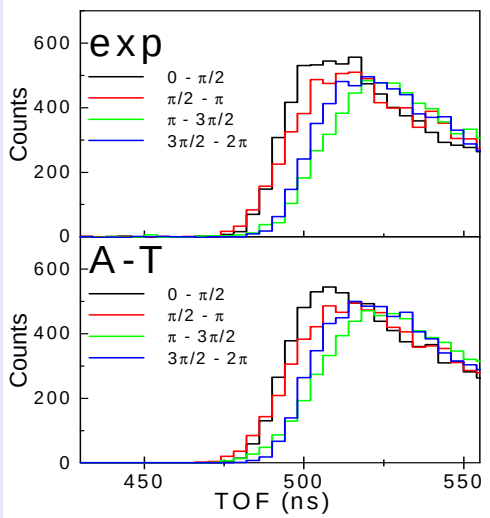
~50% bgr. reduct.



E_β - TOF correlation



RF field effect on ion TOF



Other controls:

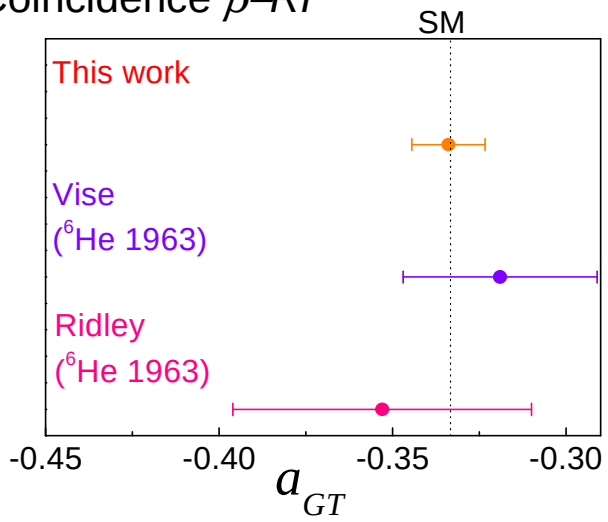
detector profiles, time in trapping cycle, stability over experiment duration…

Final result (2006 data)

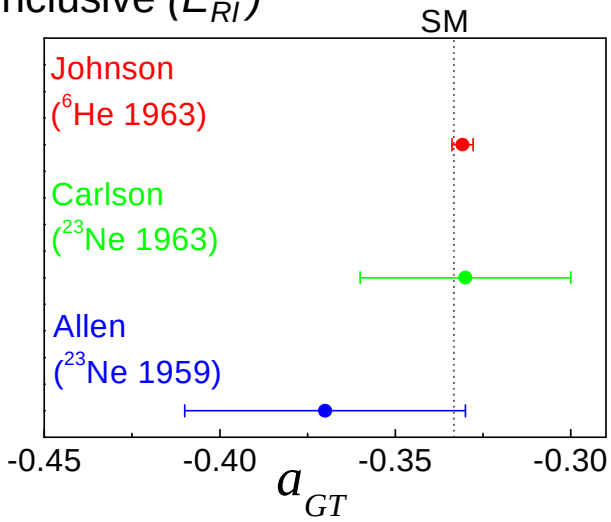
2006 experiment

Comparison with previous results

Coincidence β–RI



Inclusive (E_{RI})



Goodness-of-fit

This work:

$a_{GT} = -0.334 \pm 3.2\%$

$\chi^2/ndf = 0.915$

P-value = 0.72

Johnson:

$a_{GT} = -0.3308 \pm 0.9\%$

$\chi^2/ndf = 1.69$

P-value = 0.05

Summary

• The use of a transparent Paul trap to perform in-trap decay experiments, was demonstrated (seems to be real alternative to MOTs)

• The 2006 experiment provided the most precise measurement so far of the correlation coefficient a_{GT} in a « coincidence experiment »

• This measurement was found in agreement with SM predictions

• Analysis of data from last experiment should strongly improve the actual precision (3.2% → 0.6% relative uncertainty), and further improvements could allow to reach the 0.1 % level of precision in the coming years

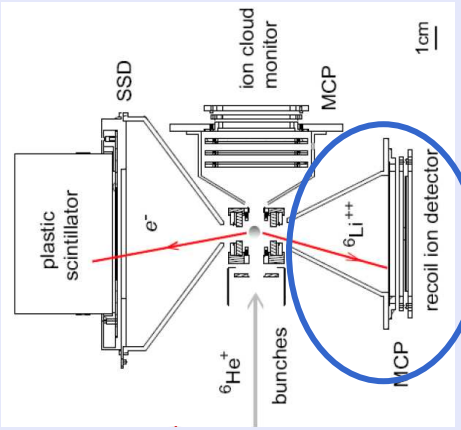
LPC-Trap:
Gilles Ban
Claire couratin
Dominique Durand
Xavier Fléchard
Etienne Liénard
François Mauger
Oscar Naviliat-Cuncic
Philippe Velten

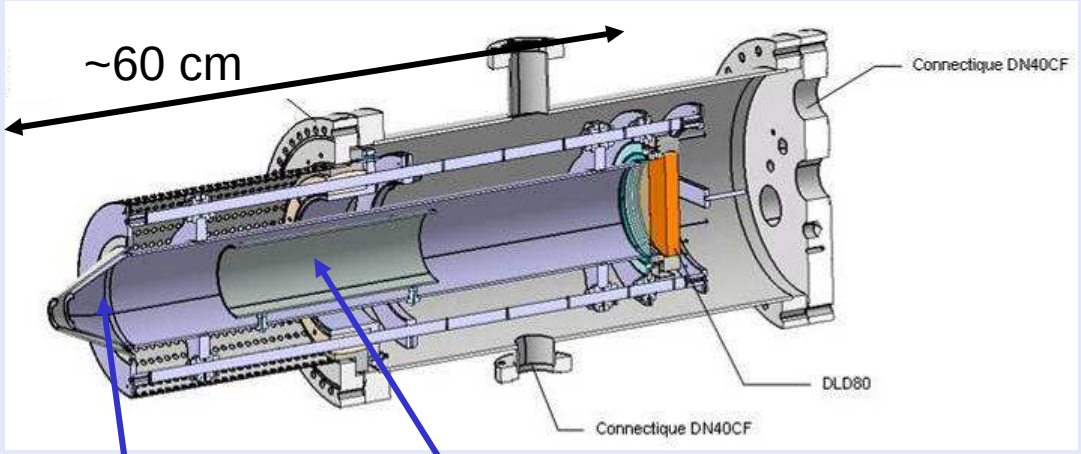
Ex-postdoc/students
Guillaume Darius
Pierre Delahaye
Mustapha Herbane
Daniel Rodriguez
Alain Mery

GANIL:
Bertrand Jacquot
Jean-Charles Thomas
…

Perspectives

Adding of acceleration electrode & longer field free region





→ *RI charge distributions separated by time of flight*

- Experiment with $^6He^+$ scheduled in November for ionization probabilities (Shake-off)
- Ionization probabilities (Shake-off) and a_{GT} measurement for ^{19}Ne and ^{35}Ar
  (Good candidates for V_{ud} determination using correlation measurements in mirror transitions)
  Naviliat & Severijns *PRL 102, 172301 (2009)*