Particle traps and β-correlations to probe weak processes in nuclei

1. Introduction
2. Brief formalism
3. Status and plans

Weak Interactions in Nuclei and Astrophysics: Standard Model and Beyond
ECT* Trento, 16 - 21 June 2003
N. Severijns
Kath. Univ. Leuven

1. Introduction – The Standard Model and beyond

Standard Model :

- works well, but still many problems as well
- SM 'low' energy (~ 200 GeV) approximation of more fundamental theory

→ search for physics beyond SM (e.g. neutrino oscillations !!)

Testing the Standard Model in the sector of the weak interaction :

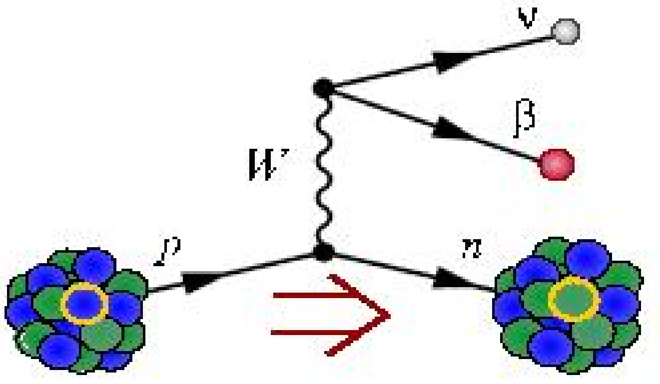
- at high energy colliders (CERN, Fermilab, DESY, ...)
- in neutrino physics (SuperKamiokande, AMANDA, ...)
- in atomic physics (e.g. parity violation)
- in nuclear beta decay (correlations, ft-values)
- ...

2. STRUCTURE OF THE WEAK INTERACTION IN NUCLEAR BETA DECAY

Fermi, 1933 : 4-fermion interaction

Lee & Yang, 1956; Wu et al., 1957 : parity violation

→ general Lorentz invariant 4-fermion interaction



$$H_\beta \propto \sum_i \bar{e}\, O_i (C_i + C_i' \gamma_5)\, \nu_e \; \langle p | O_i | n \rangle + \text{h.c.}$$

with i = Scalar, Vector, Tensor, Axial vector, Pseudoscalar

and coupling constants C_i defining properties of the interaction types

Transition probability :

distribution in energy, emission angle and polarization of β-particles
for allowed β-decay of polarized nuclei

$$dW = dW_0\, \xi \; \Big\{ 1 + \frac{\bar{p}\cdot\bar{q}}{E_e E_\nu}\, a + \frac{\Gamma m}{E_e}\, b$$

βν-correlation

Fierz interference term

$$+ \bar{J}\cdot\left[\frac{\bar{p}}{E_e} A + \frac{\bar{q}}{E_\nu} B + \frac{\bar{p}\times\bar{q}}{E_e E_\nu} D \right]$$

β-asymmetry

$$+ \bar{\sigma}\cdot\left[\frac{\bar{p}}{E_e} G + \hat{p}\,(\bar{J}\cdot\hat{p})\, Q' + \bar{J}\times\frac{\bar{p}}{E_e} R \right]$$

$$dW_0 \propto G_F^2 \;\; F(\pm Z, E_e)\,(E_e - E_0)^2\, p\, E_e\, dE\, d\Omega_e\, d\Omega_\nu$$

J.D. Jackson, S.B. Treiman, H.W. Wyld, Nucl. Phys. 4 (1957) 206 & Phys. Rev. 106 (1957) 517

with :

p, m, E_e beta-particles momentum, mass and total energy

q, E_ν neutrino momentum and total energy

J nuclear spin polarization vector

σ beta-particles spin vector

$\Gamma = \mathrm{sqrt}\,[\,1 - (\alpha Z)^2\,]$, Coulomb factor

Note: contribution from the part of the Hamiltonian involving the pseudoscalar quark current $\bar{u}\gamma_5 d$ can be neglected as it vanishes in the nonrelativistic approximation of the nucleons;

also, from $BR(\pi \to e\bar{\nu}_e)/BR(\pi \to \mu\bar{\nu}_\mu)$: $C_P < 1.25 \times 10^{-4}\, C_A$

e.g. **βν-correlation coefficient :**

$$a\xi = M_F^2 \left[|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2 \right] - \frac{1}{3} M_{GT}^2 \left[|C_A|^2 + |C'_A|^2 - |C_T|^2 - |C'_T|^2 \right]$$

with

$$\xi = M_F^2 \left[|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2 \right] + M_{GT}^2 \left[|C_A|^2 + |C'_A|^2 + |C_T|^2 + |C'_T|^2 \right]$$

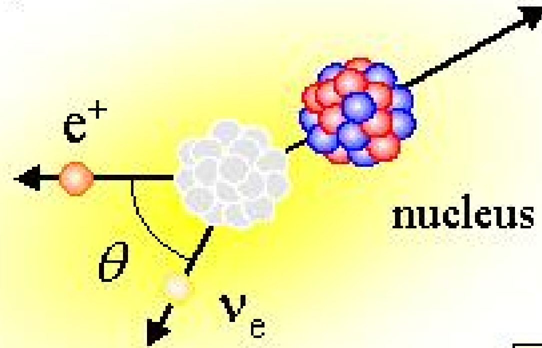
→ **independent of nuclear matrix elements if pure F or GT transition is used**

(radiative corrections : order 10^{-4} to 10^{-5} typically,
recoil corrections : order 10^{-3} to 10^{-4} ;
both to be addressed in more detail if order 10^{-3} precision is reached)

βν-correlation

$$W(\theta) = \frac{dW_0\,\xi\ \left\{1 + \frac{\bar{p}\cdot\bar{q}}{E_e E_\nu} a + \frac{\Gamma m}{E_e} b\right\}}{dW_0\,\xi\ \left\{1 + \frac{\Gamma m}{E_e} b\right\}} \Longrightarrow W(\theta) = 1 + \frac{\bar{p}\cdot\bar{q}}{E_e E_\nu}\tilde{a}$$

with $\tilde{a} \equiv \dfrac{a}{1+\dfrac{\Gamma m}{E_e} b}$



$$a_F \cong 1 - \frac{|C_S|^2 + |C_S'|^2}{|C_V|^2}$$

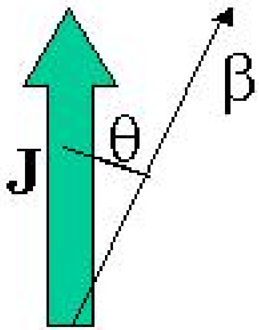
$$a_{GT} \cong -\frac{1}{3}\left[1 - \frac{|C_T|^2 + |C_T'|^2}{|C_A|^2}\right]$$

$$b_F \cong Re\ \frac{C_S + C_S'}{C_V}$$

$$b_{GT} \cong Re\ \frac{C_T + C_T'}{C_A}$$

(assuming maximal P-violation and T-invariance for V- and A-interactions)

β-asymmetry



$$W(\theta) = 1 + \bar{J}\cdot\frac{\bar{p}}{E_e}\tilde{A} \quad \text{with} \quad \tilde{A} \equiv \frac{A}{1+\frac{\Gamma m}{E_e}b}$$

for a pure Gamow-Teller transition :

$$\tilde{A}_{GT} \cong \mp 1 + \frac{\alpha Z m}{p_e}\,\mathrm{Im}\left(\frac{C_T + C_T'}{C_A}\right) \pm \frac{\Gamma m}{E_e}\,\mathrm{Re}\left(\frac{C_T + C_T'}{C_A}\right)$$

(assuming maximal P-violation and T-invariance for V- and A-interactions)

In the Standard Model :

* $C_V = 1$
* $C_A = -1.26$
* $C_V' = C_V$ and $C_A' = C_A$

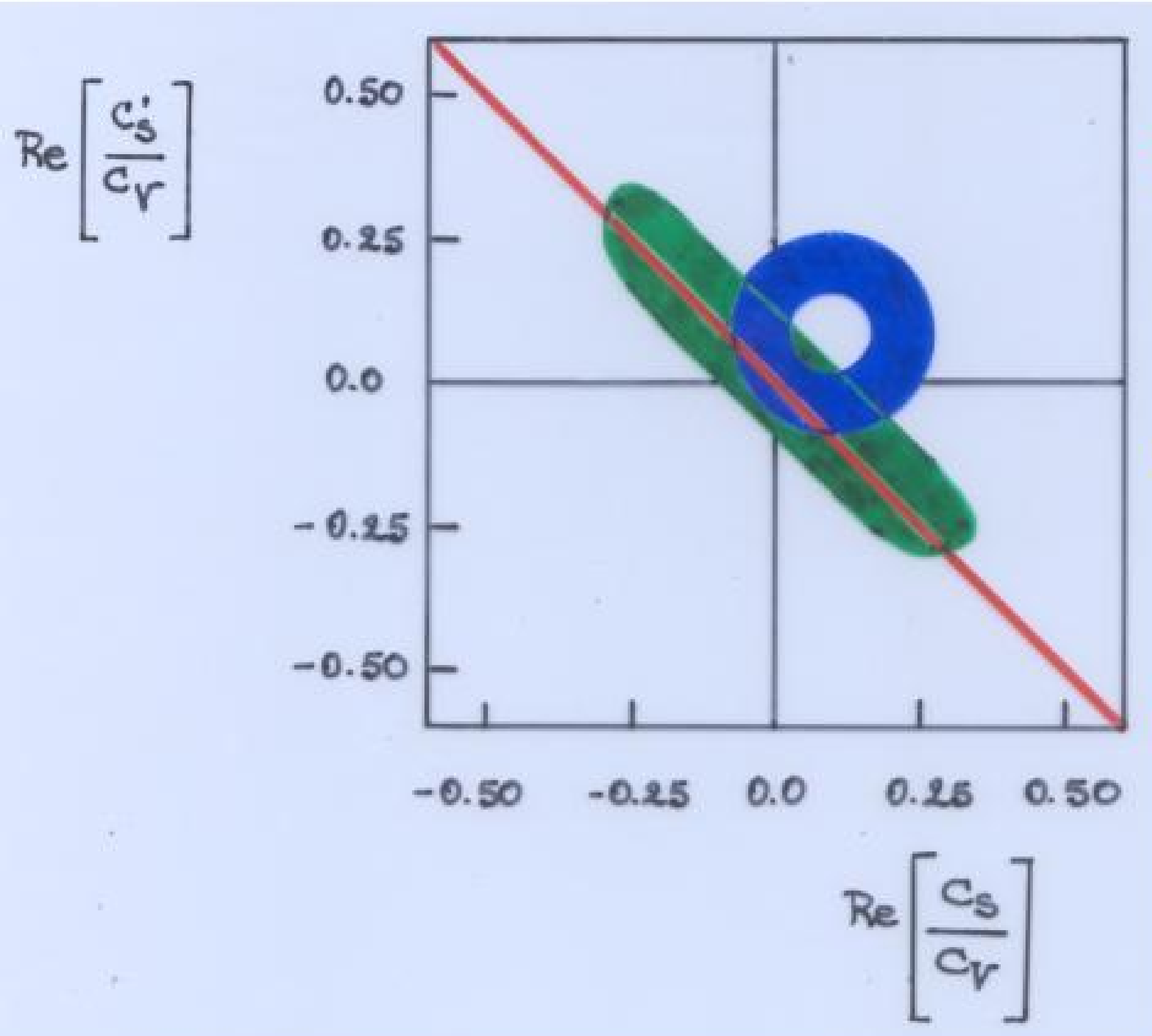
* $C_S = C_S' = C_T = C_T' = C_P = C_P' \equiv 0$

  experimental upper limits:

  $$\left|\frac{C_T}{C_V}\right| < 0.13 \qquad \left|\frac{C_S}{C_V}\right| < 0.08 \qquad 95\%\text{CL}$$

* no time reversal violation (except for the CP-violation described by the phase in the CKM quark-mixing matrix)

Present β-decay limits on scalar currents



green:

neutron decay experiments,

positron polarization (unpol. nuclei)

Fierz interference term in ^{22}Na & ^{6}He

blue :

βν-correlation, ^{32}Ar

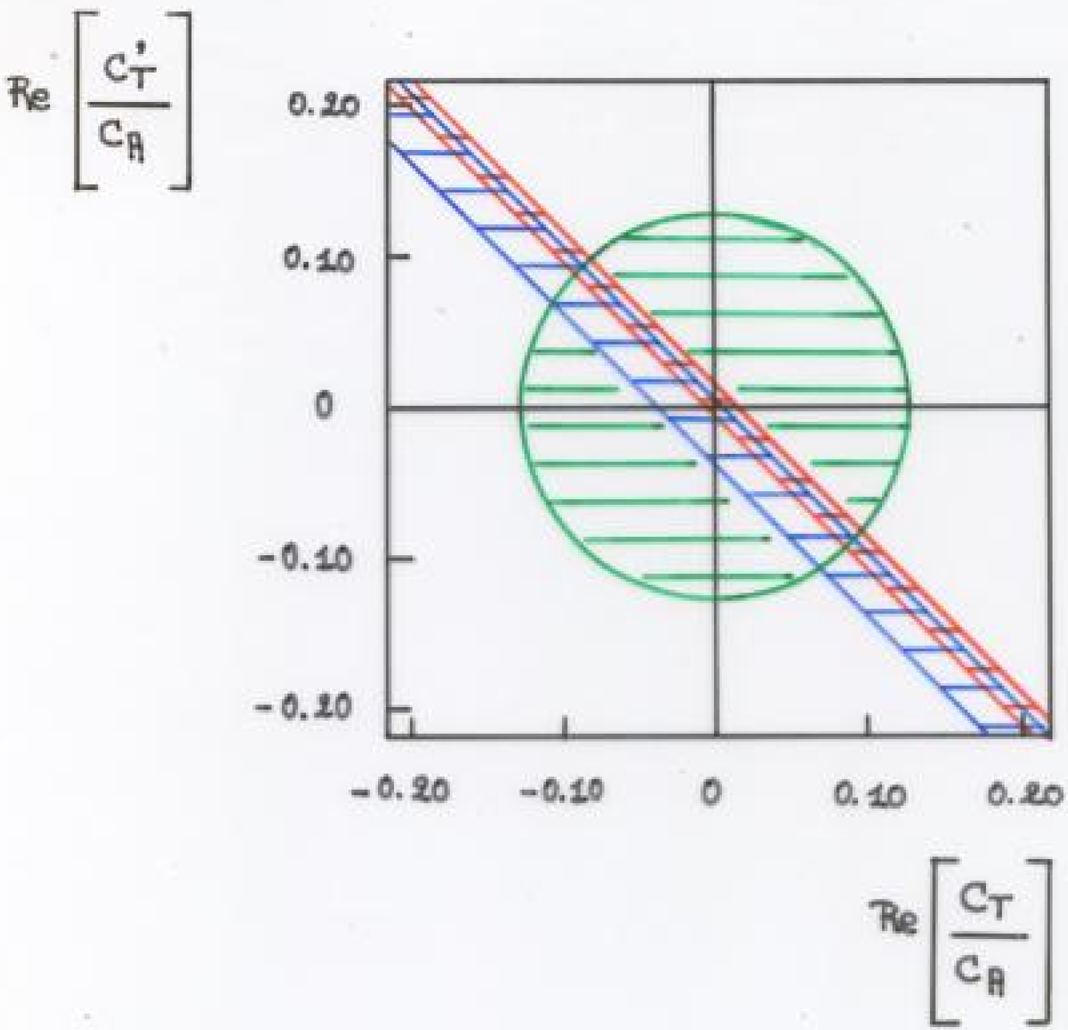
Adelberger et al., Phys. Rev. Lett. 83 (1999)

red :

Ft-value of superallowed Fermi transitions

I.S. Towner, J.C. Hardy, J.Phys. G: Nucl. Part. Phys. 29 (2003) 197

Present β-decay limits on tensor currents



green:

βν-correlation, ^{6}He

Johnson et al., Phys.Rev. 132 (1963) 1149

blue :

positron polarization, ^{107}In

Severijns et al., Nucl. Phys. A629 (1998) 423c

red :

all other relevant experiments

P.A. Quin et al., Phys. Rev. D47 (1993) 1247

Limits (95 % CL) on possible new bosons for S- and T-interactions, from high-energies:

mass limit for $H^{\pm}$ (charged Higgs) : > 71.5 GeV (LEP)

mass limit for leptoquarks : > 242 GeV (from pair production; combined CDF-D0)

: > 290 GeV (from single production; H1)

Sensitivity of beta-neutrino correlation (95 % CL) :

$\Delta a = 0.01 \rightarrow$ sensitive to masses of new bosons of $\sim (0.01)^{-1/4} M_W \approx 215$ GeV/c^2

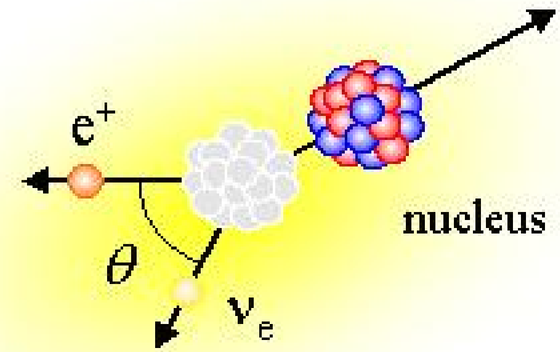
$\Delta a = 0.005 \rightarrow$ sensitive to masses of new bosons of $\sim (0.005)^{-1/4} M_W \approx 255$ GeV/c^2

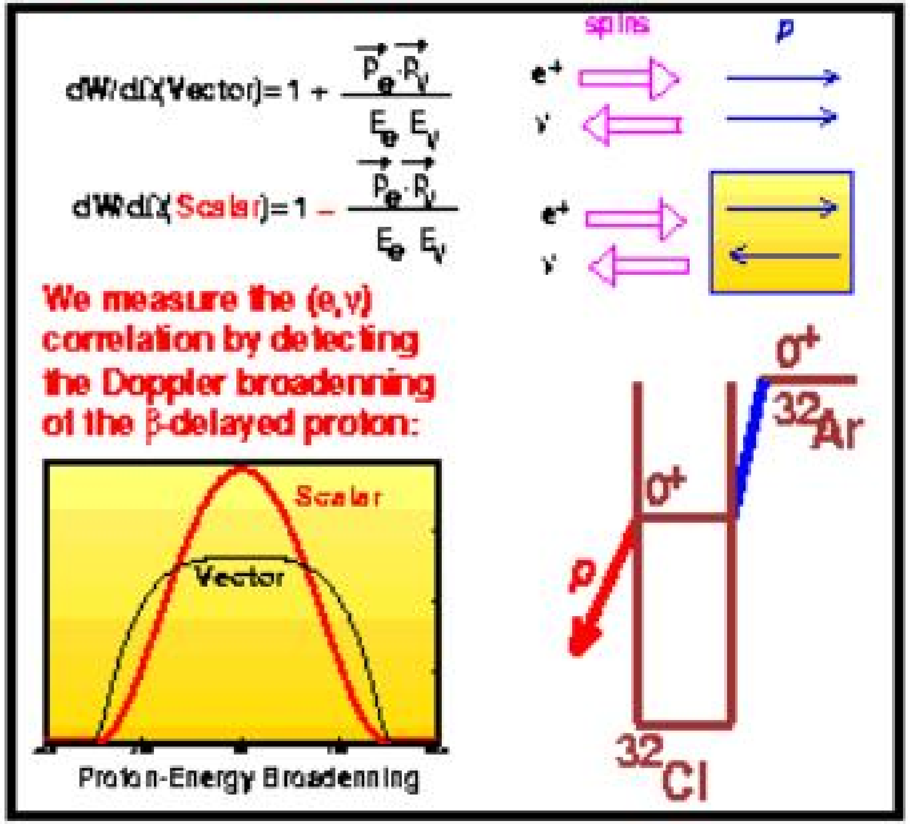
$\Delta a = 0.002 \rightarrow$ sensitive to masses of new bosons of $\sim (0.002)^{-1/4} M_W \approx 320$ GeV/c^2
("handwaving")

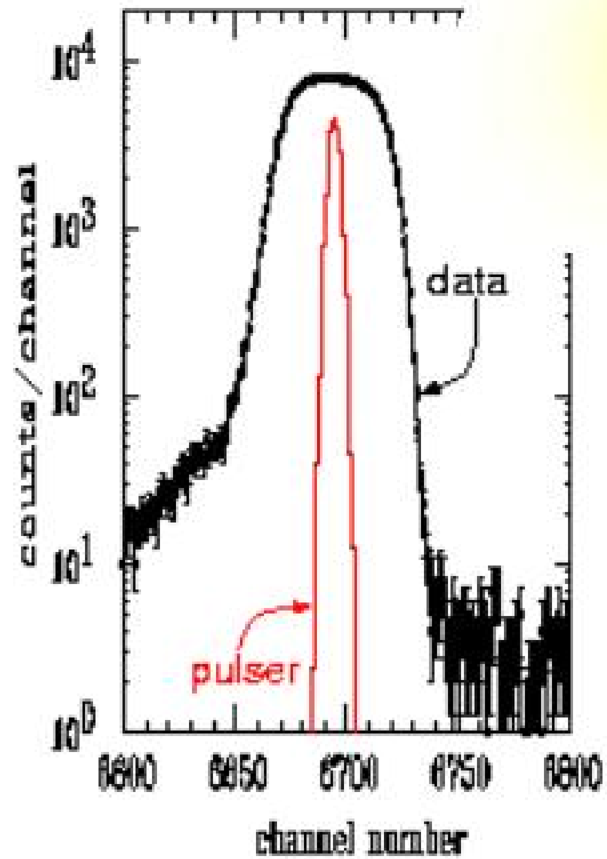
Also, it always makes sense to carry out tests of the SM in different energy domains.

(e,ν) correlation in the β decay of 32Ar

E.G. Adelberger, C. Ortiz, A. Garcia, H.E. Swanson, M. Beck, O. Tengblad, M.J.G. Borge, I Martel, H. Bichsel, and the ISOLDE collaboration, PRL 83, 1299 (1999).







$$\tilde{a} = 0.9989 \pm 0.0052(\text{stat}) \pm 0.0039\ (\text{syst}) \quad \rightarrow \quad \tilde{a} = 1.0050 \pm 0.0052(\text{stat}) \pm (\text{syst})$$

after measurement of ^{32}Ar mass (K. Blaum et al., subm. to PRL)

3. Traps for weak interaction physics

Ion and atom traps
provide ideal sources for
weak interaction tests
in nuclear beta decay :

- sample is isotopically pure
- localized in small volume
- source scattering negligible
- atoms/ions decay at rest
- potential for polarized sample

Traps for weak interaction physics :

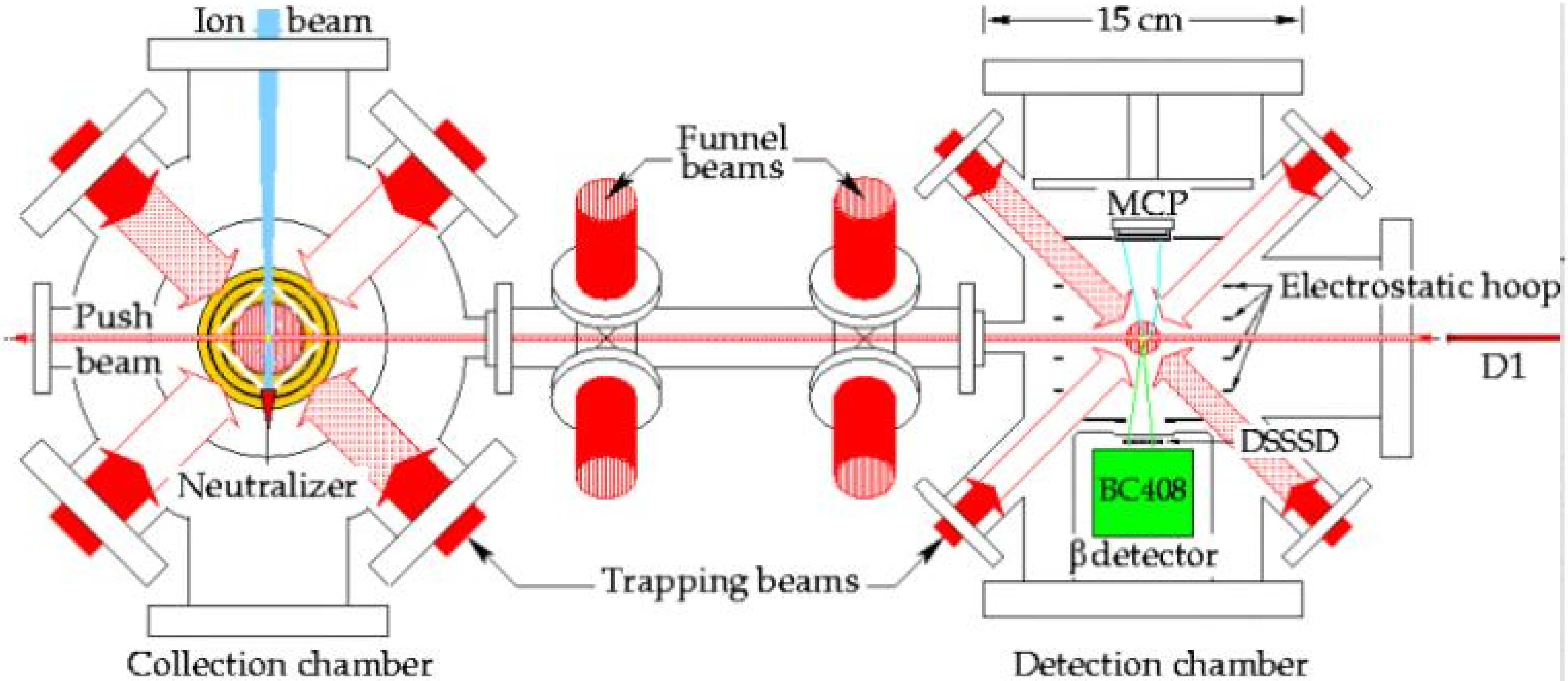
1. Atom traps :

- **TRIUMF-ISAC, ^{38m}K, βν-correlation (J. Behr et al.)**
  A. Gorelov et al., Hyperfine Interactions 127 (2000) 373
- **LBNL & UC Berkeley, ^{21}Na, βν-correlation (S.J. Freedman et al.)**
  N. Scielzo, Ph. D. Thesis (2003)
- **LANL Los Alamos, ^{82}Rb, β-asymmetry (D. Vieira et al.)**
  S.G. Crane et al., Phys. Rev. Lett. 86 (2001) 2967
- **KVI-Groningen, Na, Ne, Mg, D-coefficient (K. Jungmann et al.)**
- **...**

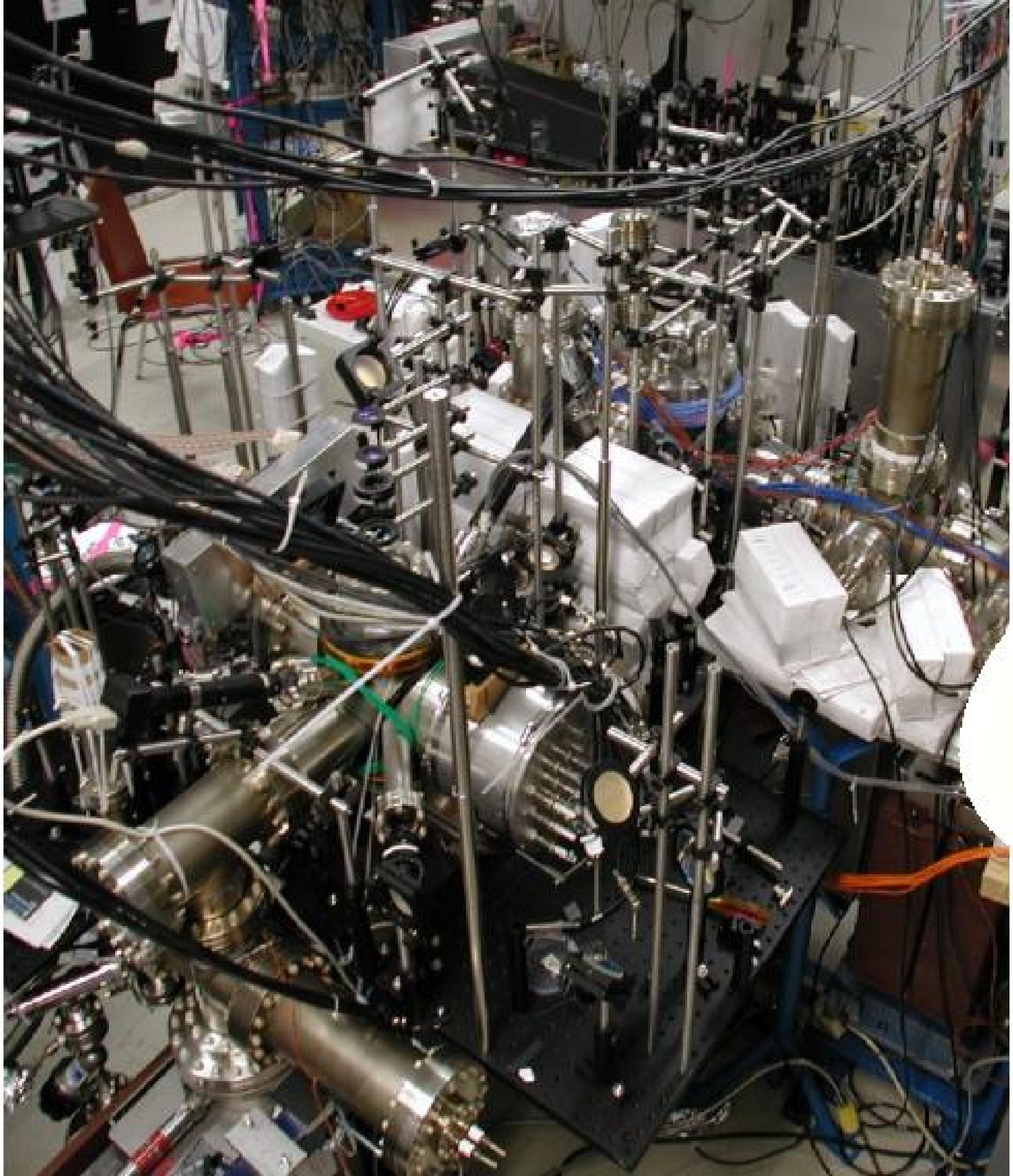
2. Ion traps :

- **LPC-Caen, ^{6}He, βν-correlation (O. Naviliat-Cuncic et al.)**
  P. Delahaye et al., Hyperfine Interactions 132 (2001) 479
- **Leuven, ^{35}Ar, βν-correlation (N. Severijns et al.)**
  D. Beck et al., Nucl. Inst. Methods Phys. Res., A 503 (2003) 567
- **ISOLTRAP-CERN, mass for 0+ → 0+ decays (H.-J. Kluge et al.)**
- **...**

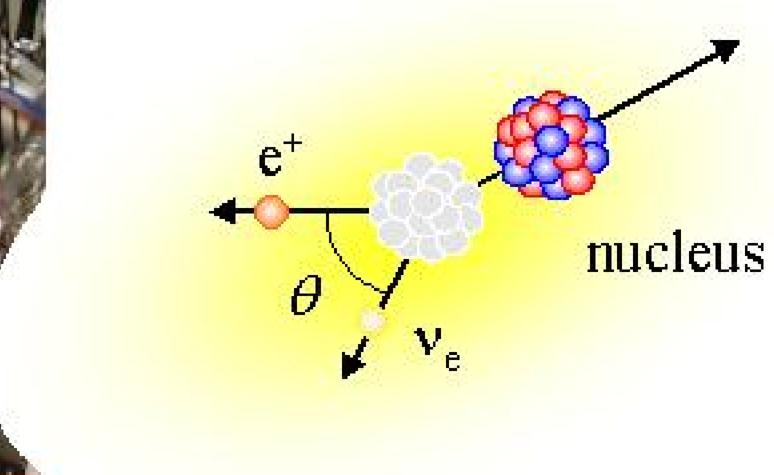
TRIUMF Neutral Atom Trap



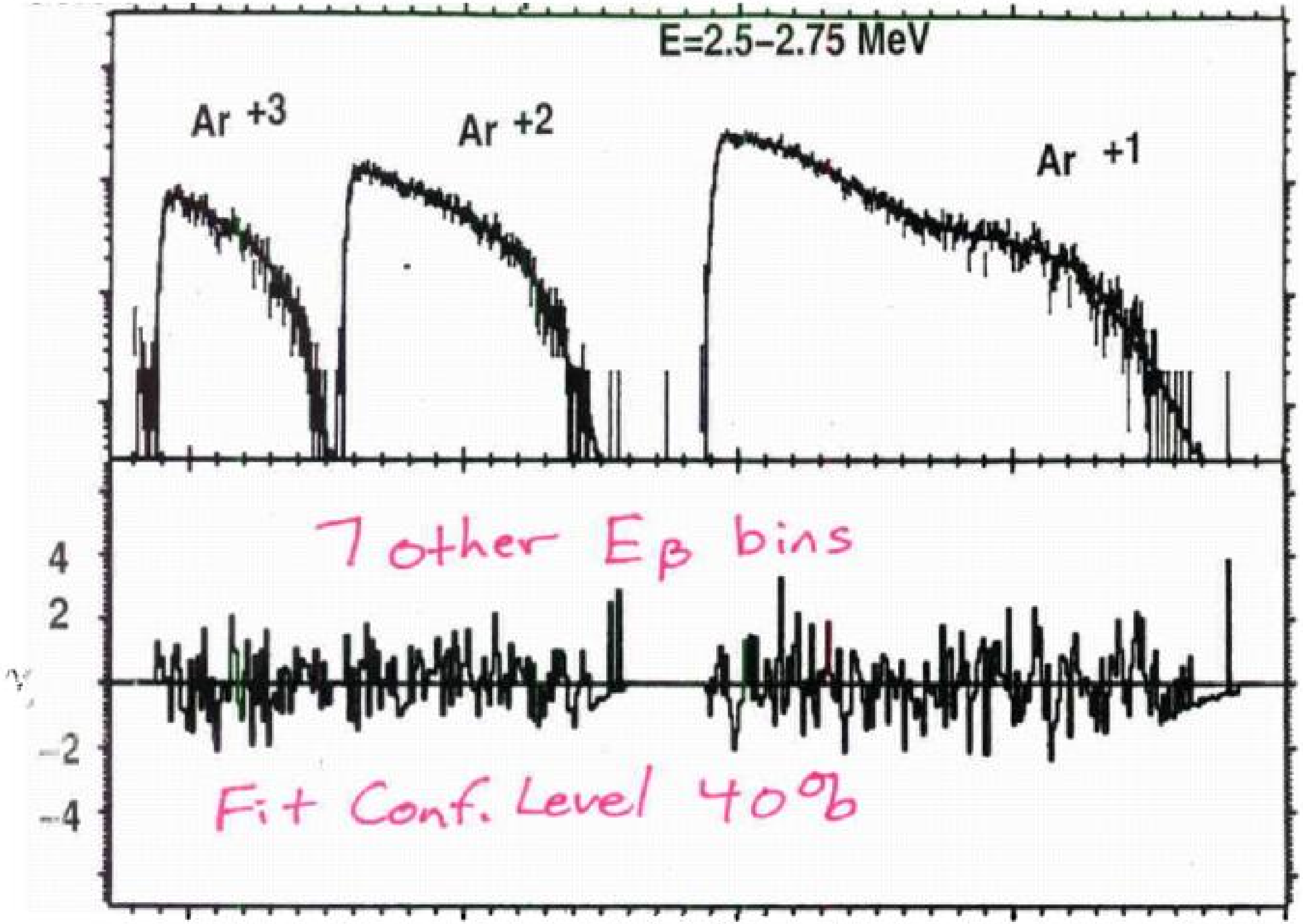
A. Gorelov et al., Hyperfine Interactions 127 (2000) 373



TRIUMF
neutral atom trap



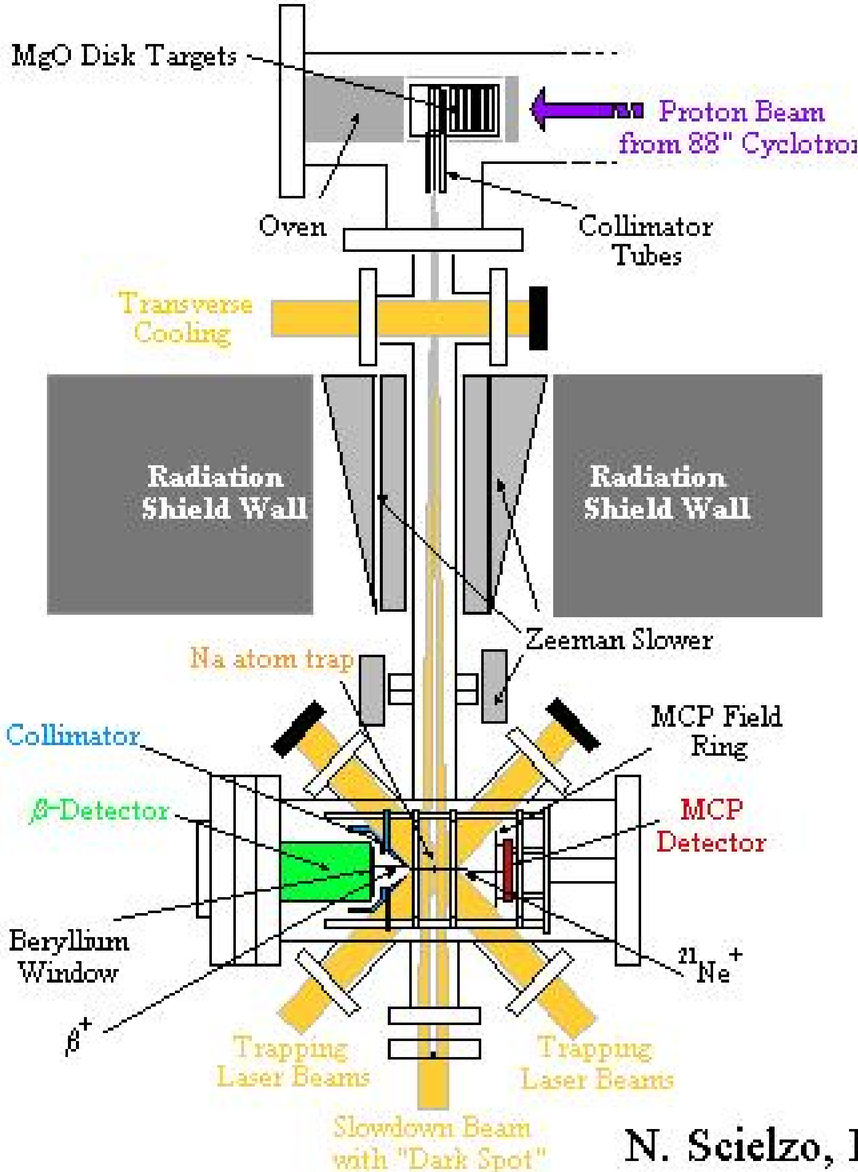
J. Behr et al.



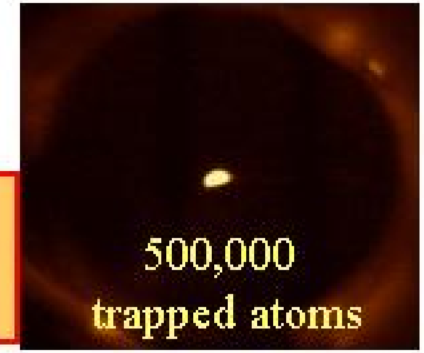
First result available in autumn 2003 (expected)

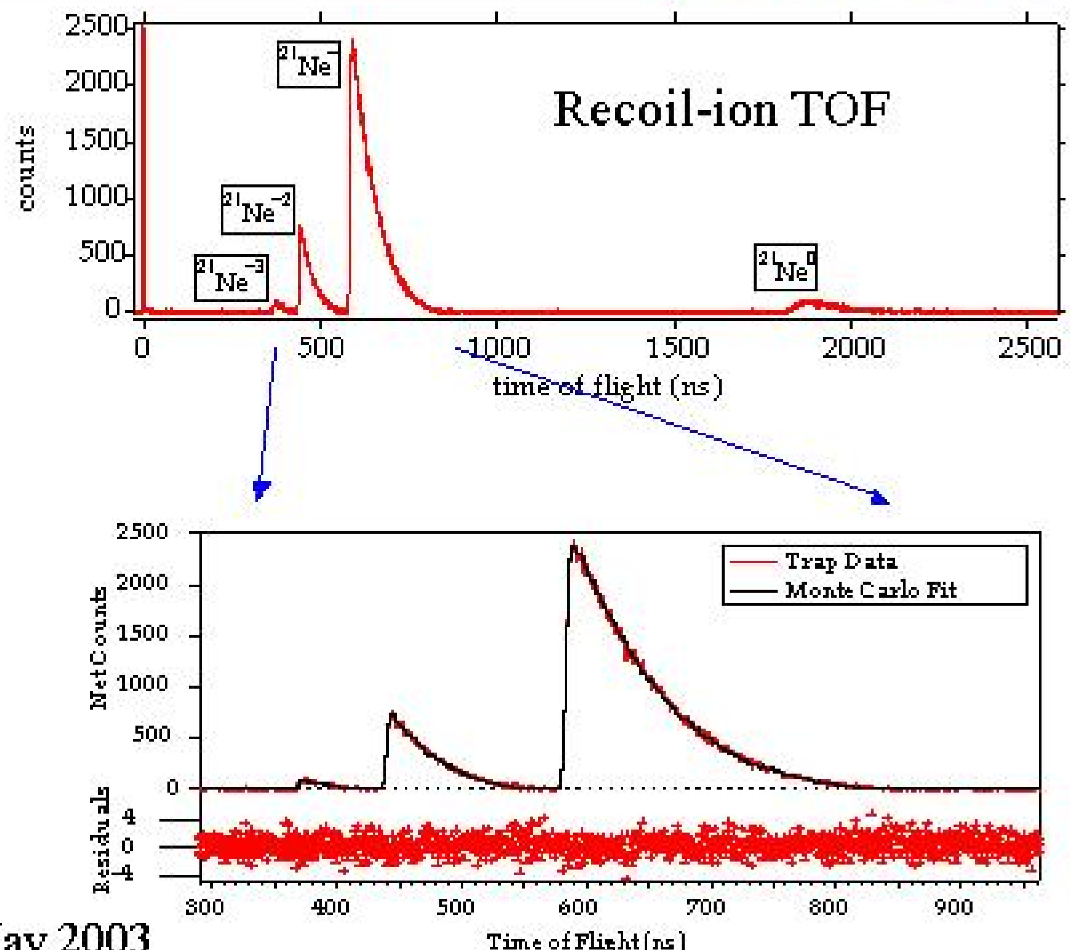
Measuring the β–ν Angular Correlation in Magneto-Optically Trapped ^{21}Na

S. J. Freedman, B. K. Fujikawa, N. D. Scielzo, and P. A. Vetter
UC Berkeley and Nuclear Science Division, LBNL



Result: $a_{exp} = 0.5243 \pm 0.0092$
$a_{SM} = 0.558 \pm 0.003$

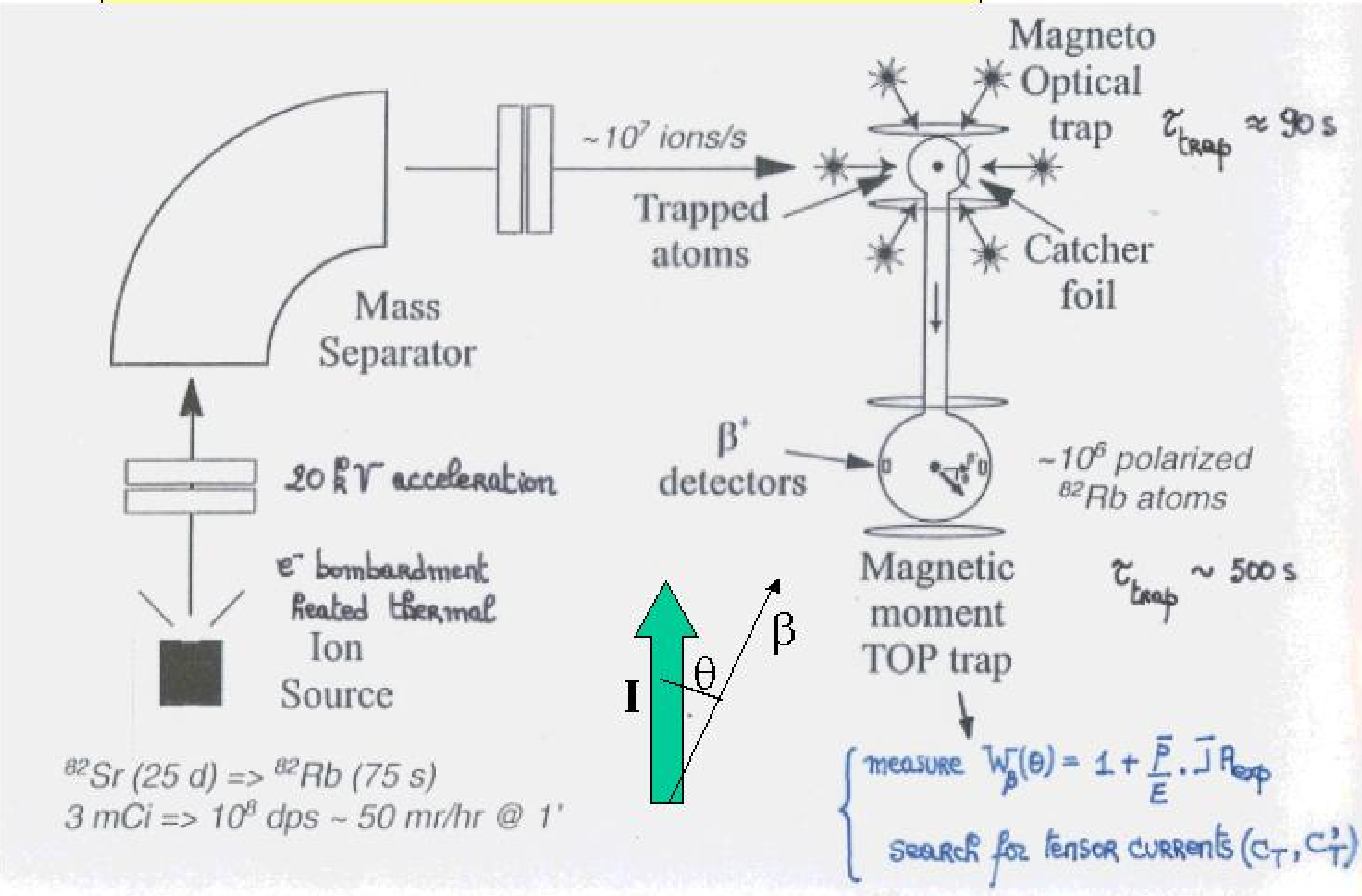




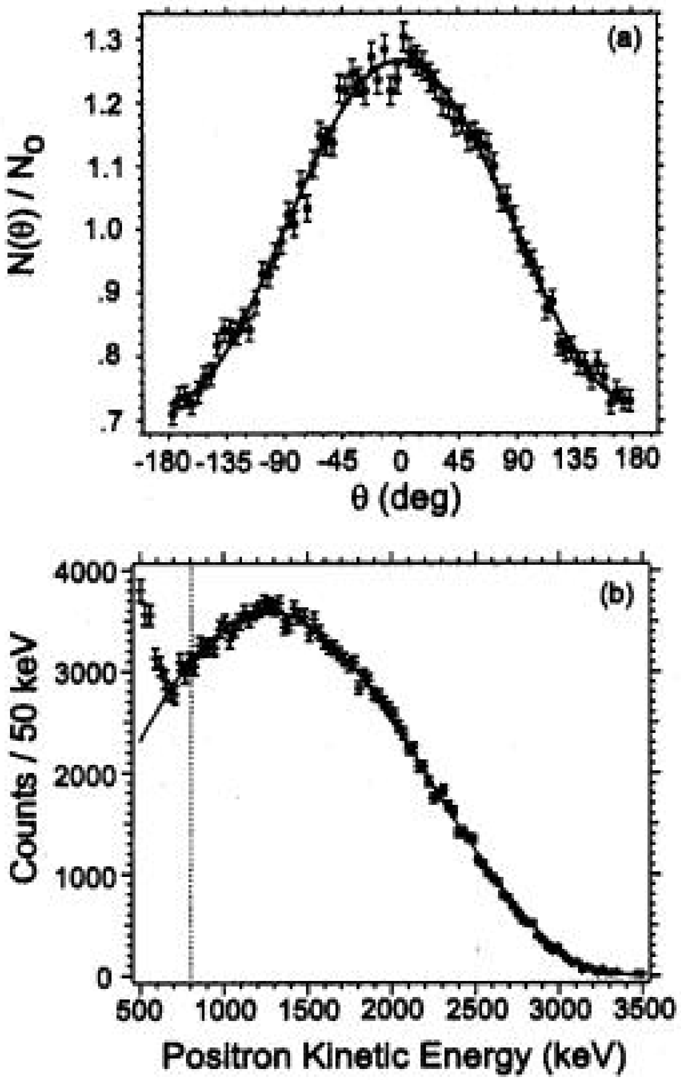
N. Scielzo, Ph.D. May 2003

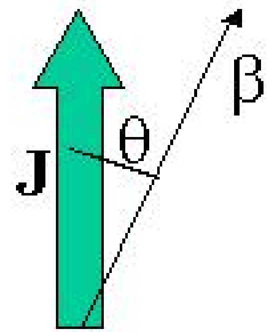
The atom trap at Los Alamos - LANL

D. Vieira et al.



angular distribution ↓



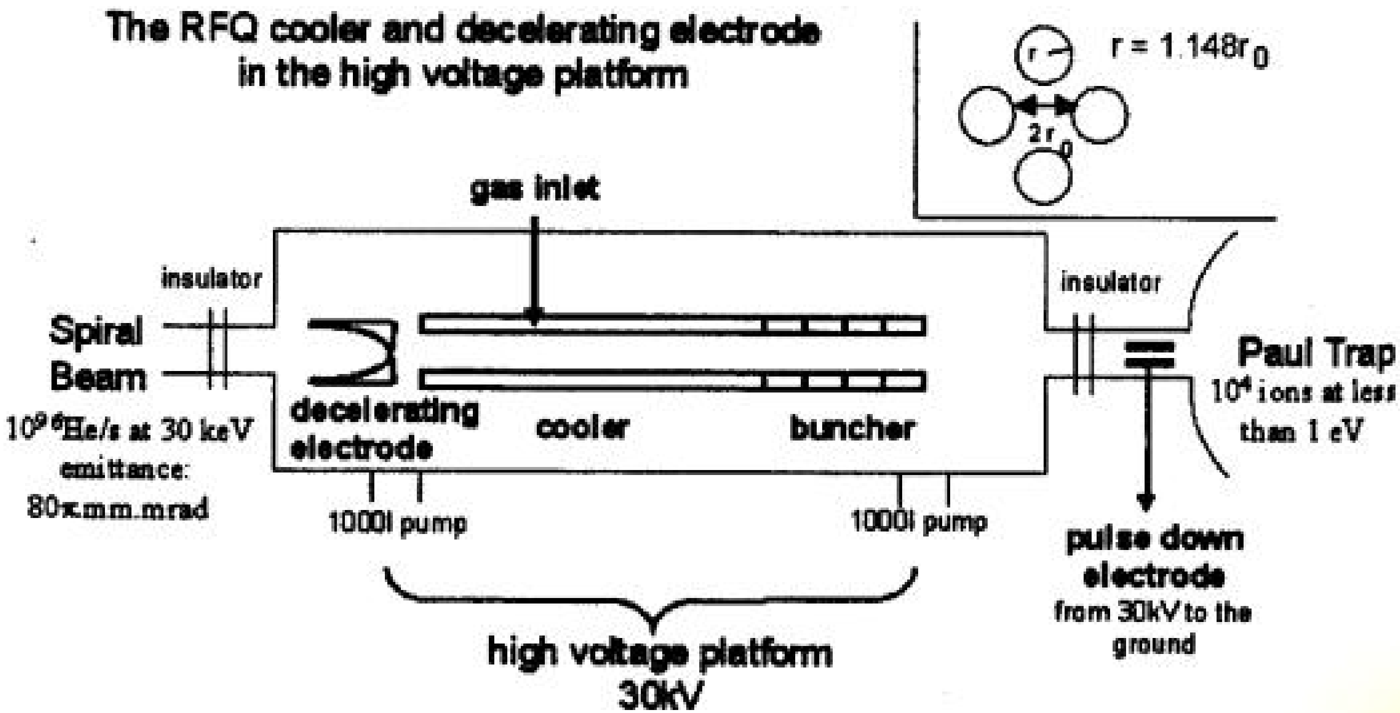


D.J. Vieira et al., Hyp.Int. 127 (2000) 387

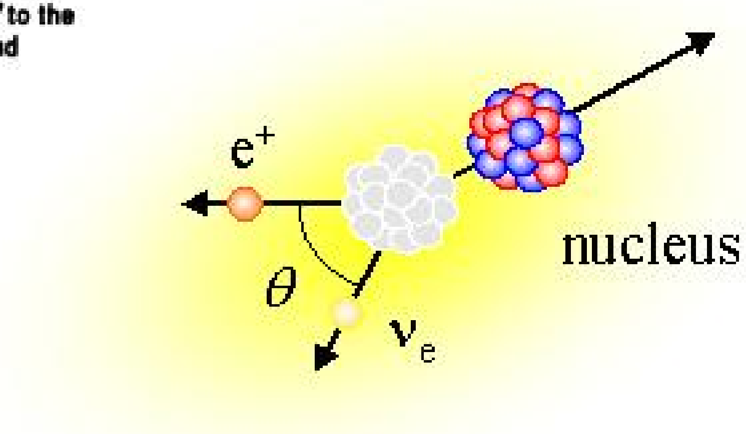
S.G. Crane et al., Phys. Rev. Lett. 86 (2001) 2967 (first results)

positron energy spectrum ↑

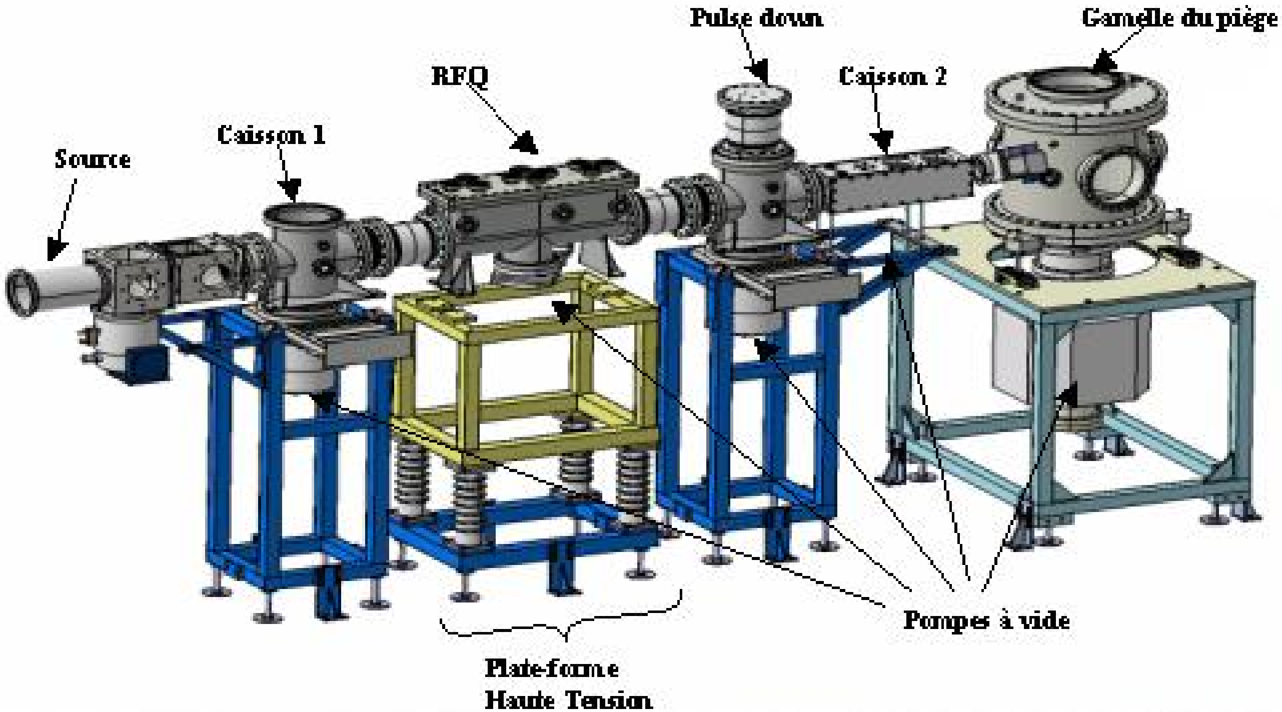
The LPC-Caen Paul trap

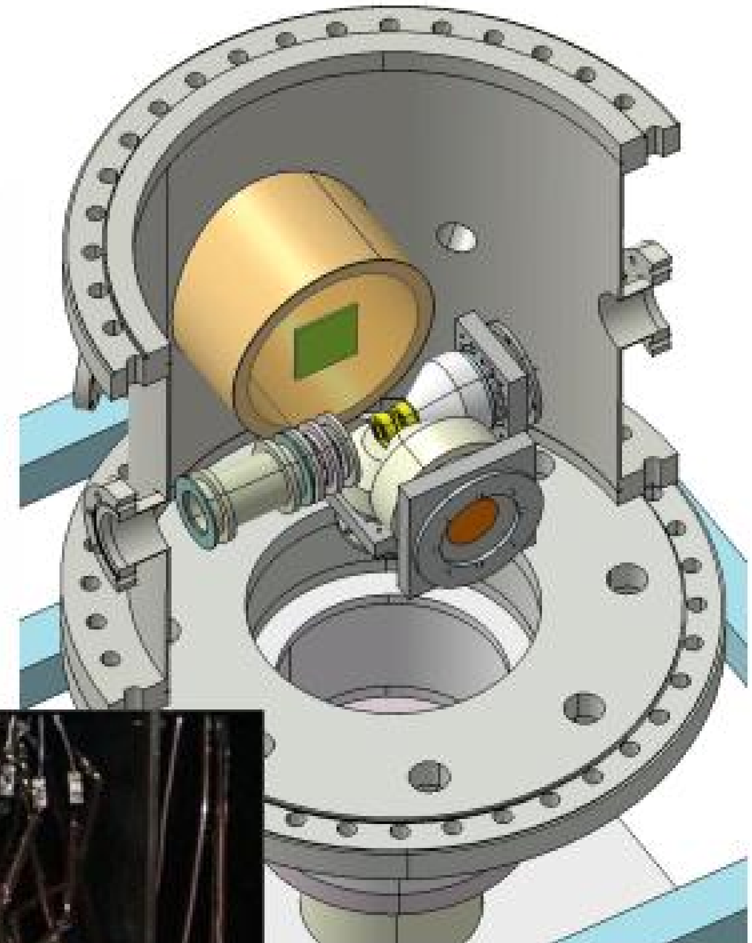


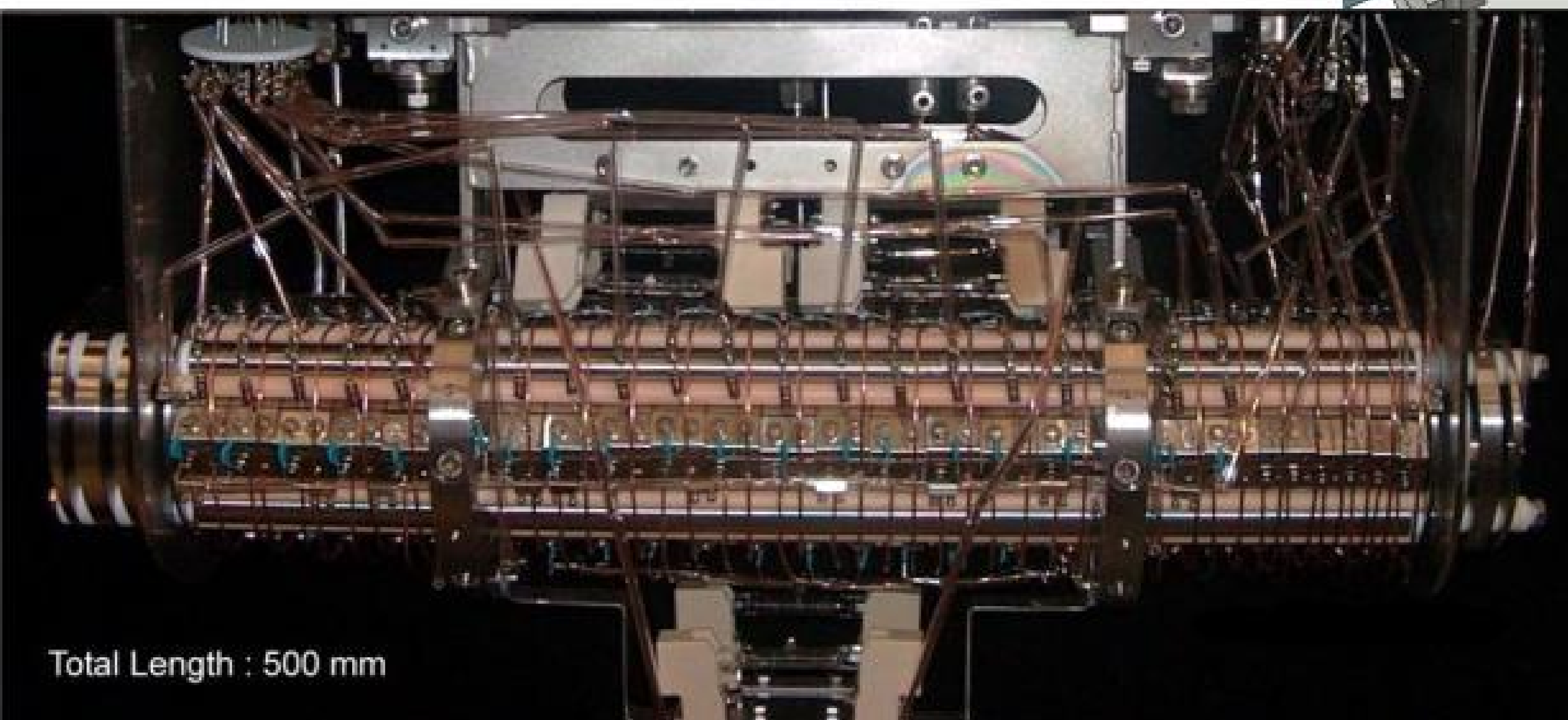
- measure $\beta\nu$-correlation with ^{6}He
- cool ^{6}He with hydrogen gas
- to be installed at SPIRAL



P. Delahaye et al., Hyperfine Interactions 132 (2001) 479







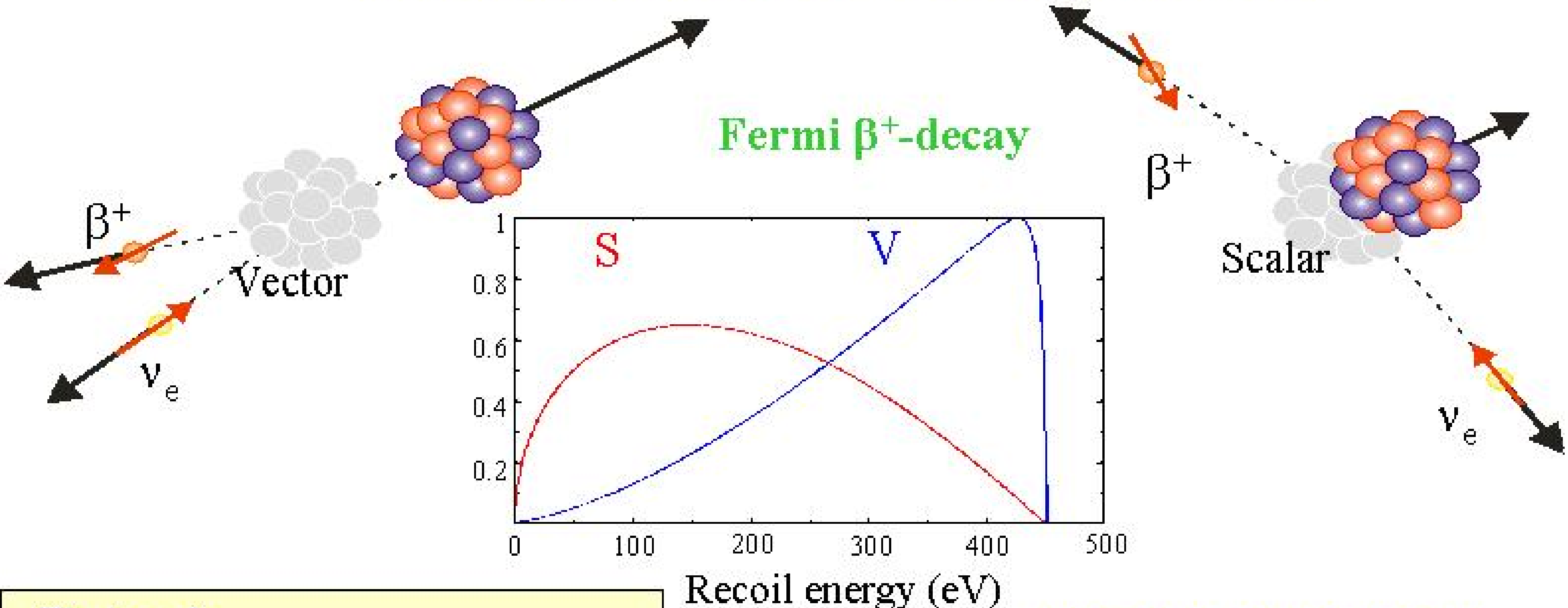
First experiment
expected in 2004

LPC Paul trap set-up
O. Naviliat-Cuncic et al.

WITCH – Weak Interaction Trap for CHarged particles

ISOLDE-CERN (K.U.Leuven, Univ. Munchen, CERN)

cooler & decay Penning trap + retardation spectrometer



First goal :

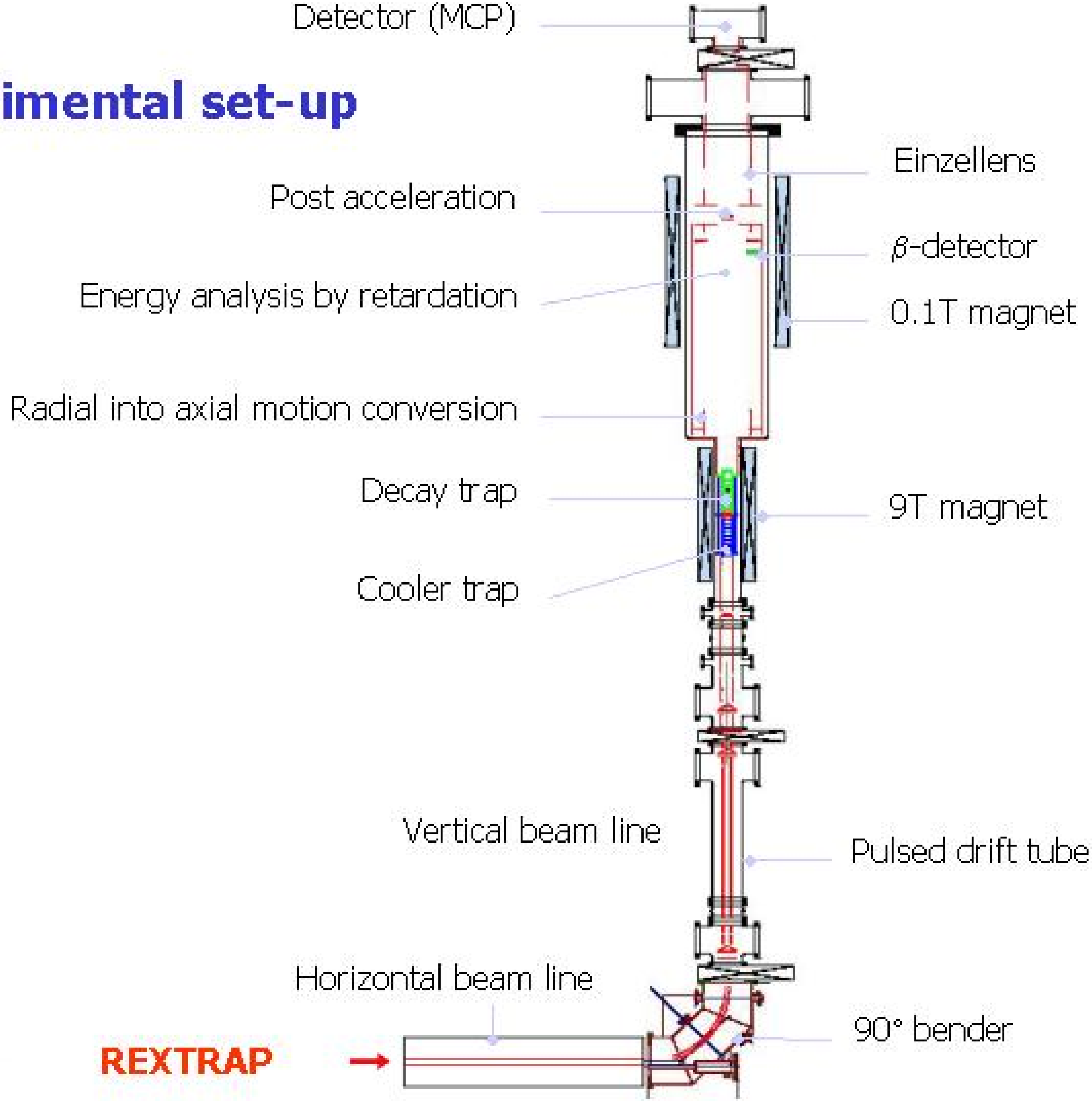
search for scalar weak interaction by measuring shape of recoil ion energy spectrum after β-decay

First experiment expected in 2004

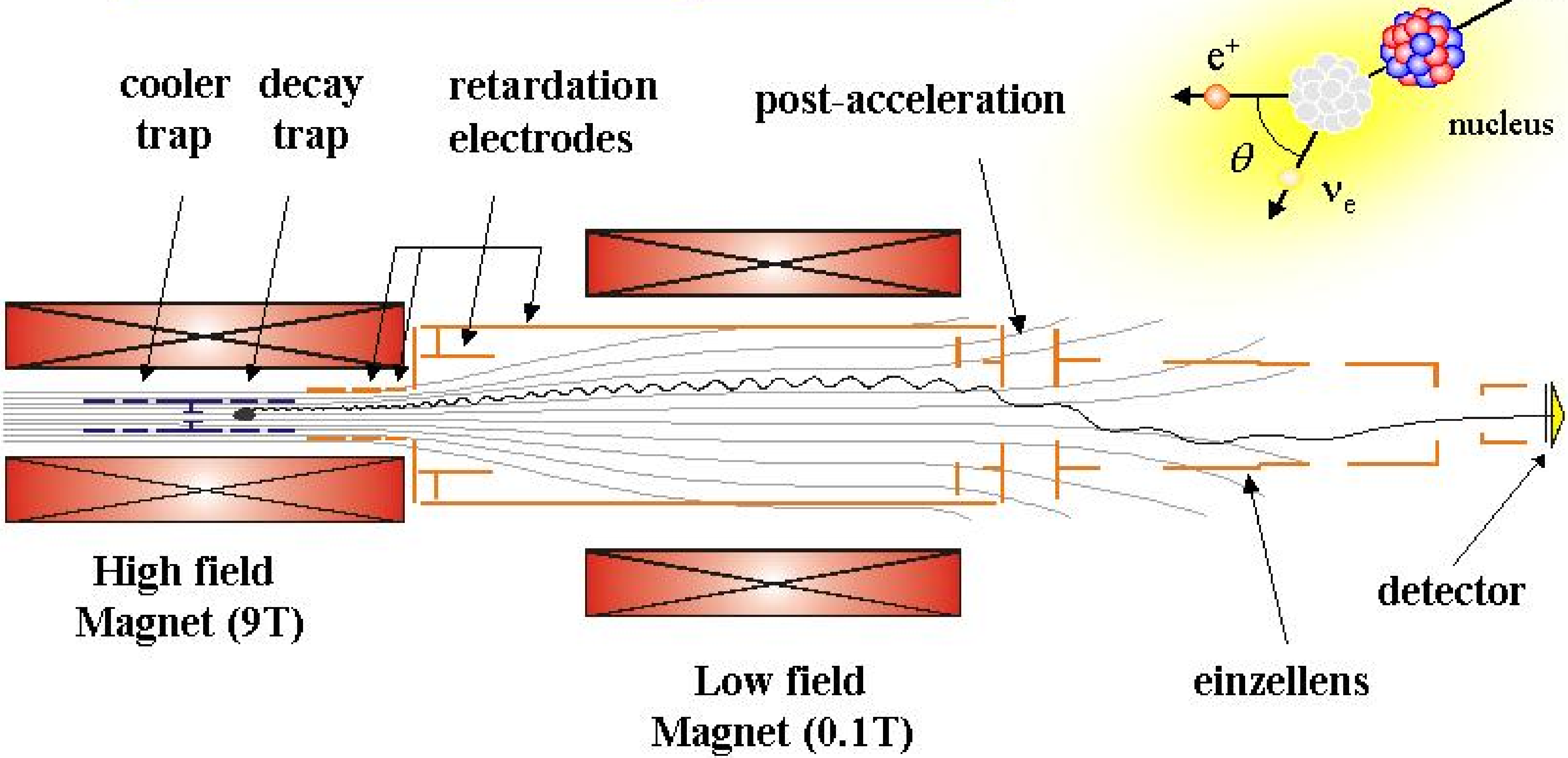
Other physics possibilities :

- **in-trap beta spectroscopy**
- **determination of EC/β^+ ratios**
- **determination of Q_β-values**
- **measure charge state distributions**

Experimental set-up



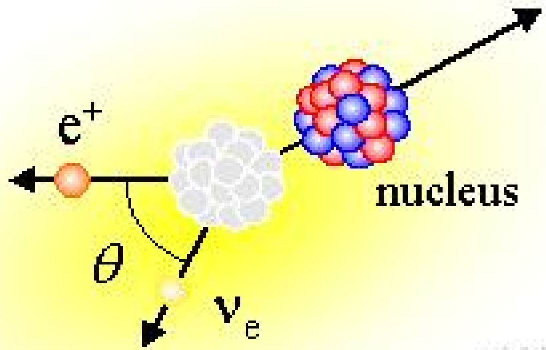
WITCH retardation spectrometer



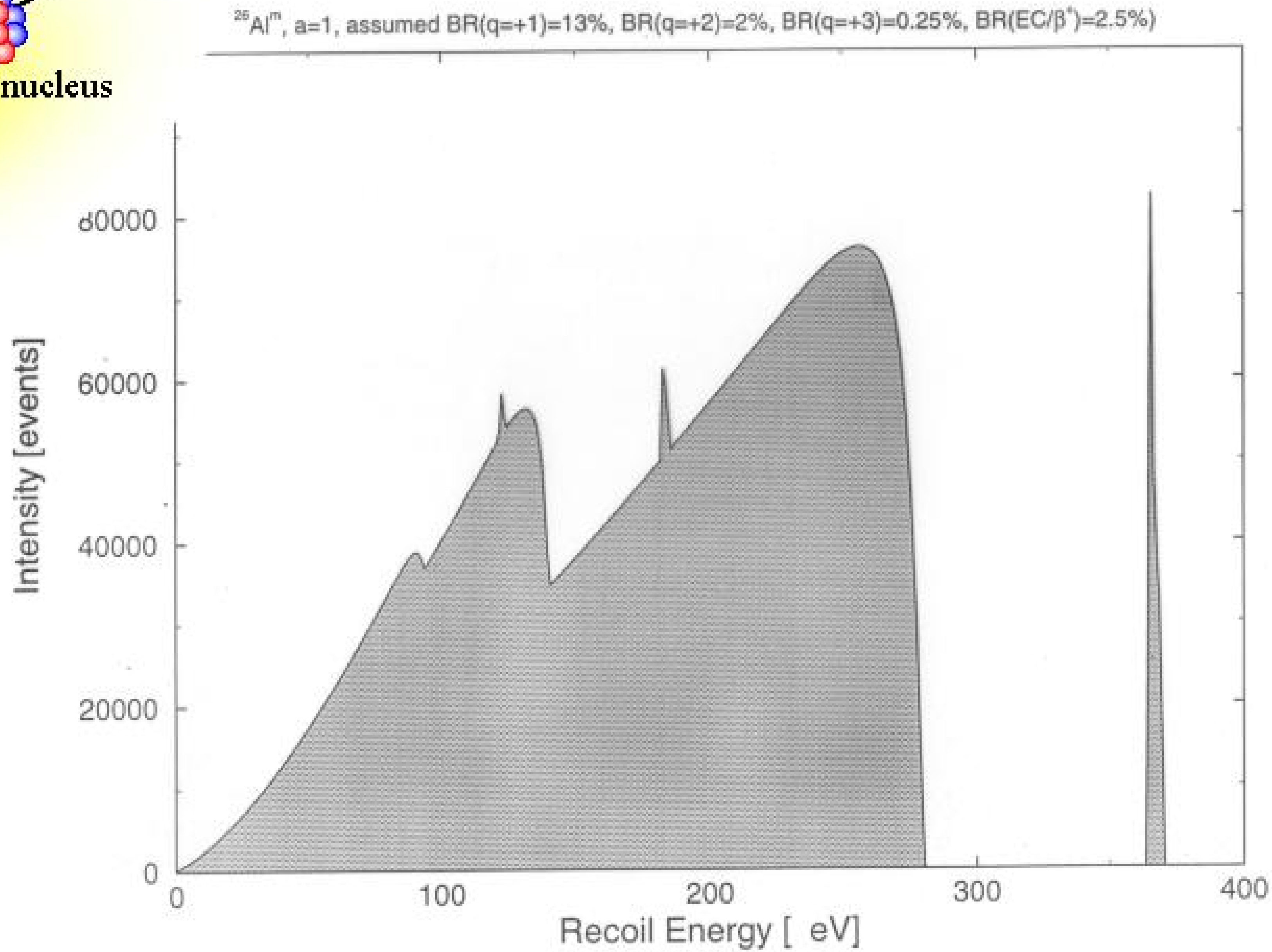
Energy conversion

$$\frac{E_{\perp 1}^{kin}}{E_{\perp 0}^{kin}} = \frac{B_1}{B_0} = \frac{0.1T}{9T} = 1.1\%$$

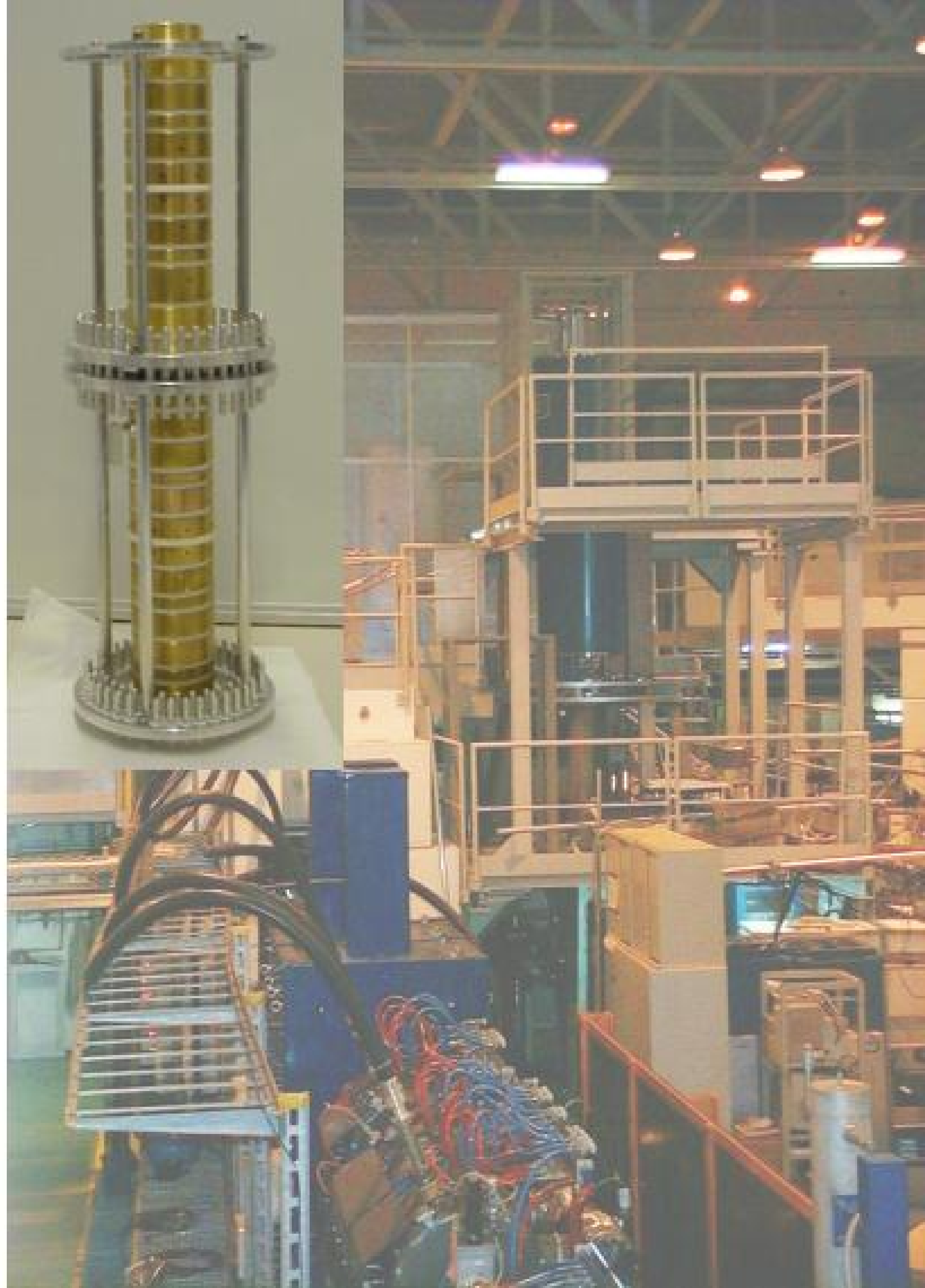
What we expect to see :



Full Recoil Energy Spectrum




WITCH



Experiments not using traps (all in preparation) :

1. Neutron decay

- *a*spect spectrometer (Mainz, München, ILL) / *a*-coefficient
  O. Zimmer et al., Nucl. Instr. Meth. A 440 (200) 548

- PERKEO-II (Heidelberg, ILL) / *A*-coefficient
  H. Abele et al.

2. Nuclear β-decay

- 32Ar (LPC-Caen, GANIL) / *a*-coefficient
  O. Naviliat-Cuncic et al.

- polarized nuclei (Leuven, ISOLDE-CERN) / *A*-coefficient
  N. Severijns et al.

3. The unitarity problem : $\sum V_{ui}^2 = V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$?

V_{ud} :

a. *Ft* ($0^+ \rightarrow 0^+$)

$$Ft = ft(1+\delta_R)(1-\delta_c) = \frac{K}{2G_F^2 V_{ud}^2 (1+\Delta_R)} \rightarrow \sum V_{ui}^2 = 0.9969(15)$$

b. neutron decay (τ_n and *A*)

world average values $\rightarrow \sum V_{ui}^2 = 0.9961(24)$

only most precise *A*-result $\rightarrow \sum V_{ui}^2 = 0.9917(28)$

c. pion β-decay : $\sum V_{ui}^2 = 1.0030(110)$

based on V_{us} = 0.2196(26) from K_{e3} decay ($K^+ \rightarrow \pi^0 e^+ \nu_e$) **(late 1970's data)**

New BNL-data : **V_{us} = 0.2272(20)(7)(18)** **from K_{e3} decay (Ph.D. thesis A. Sher)**

$\rightarrow$ $\sum V_{ui}^2 = 1.0003(16)$ **(for $0^+ \rightarrow 0^+$) and** $\sum V_{ui}^2 = 0.9995(25)$ **(for neutron) !!!**

→ New BNL data for V_{us} (need to be confirmed) solve unitarity problem !!