

Stéphanie Roccia

# LTNO in Europe

—Low Temperature Nuclear Orientation—

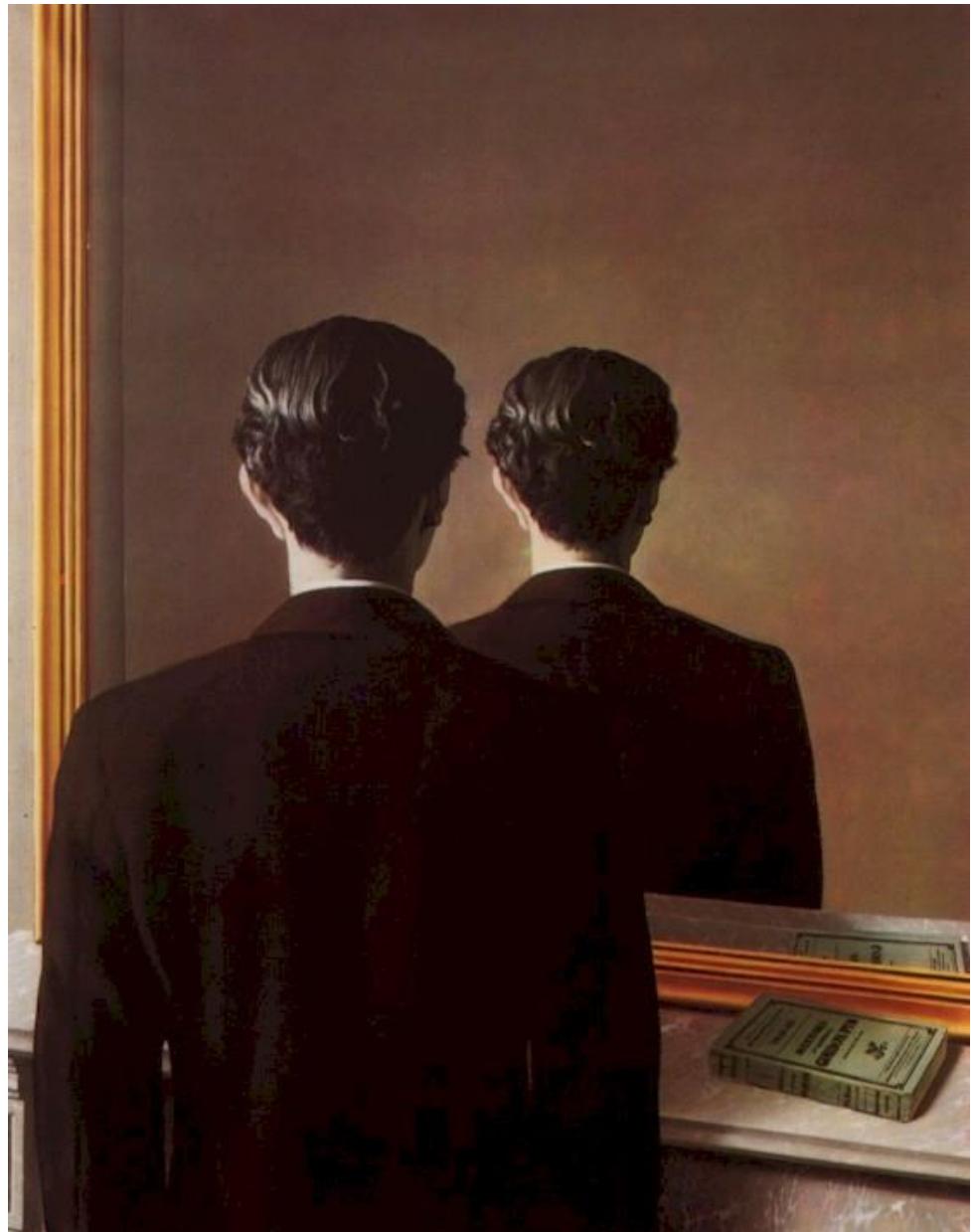


Comprendre le monde,  
construire l'avenir®

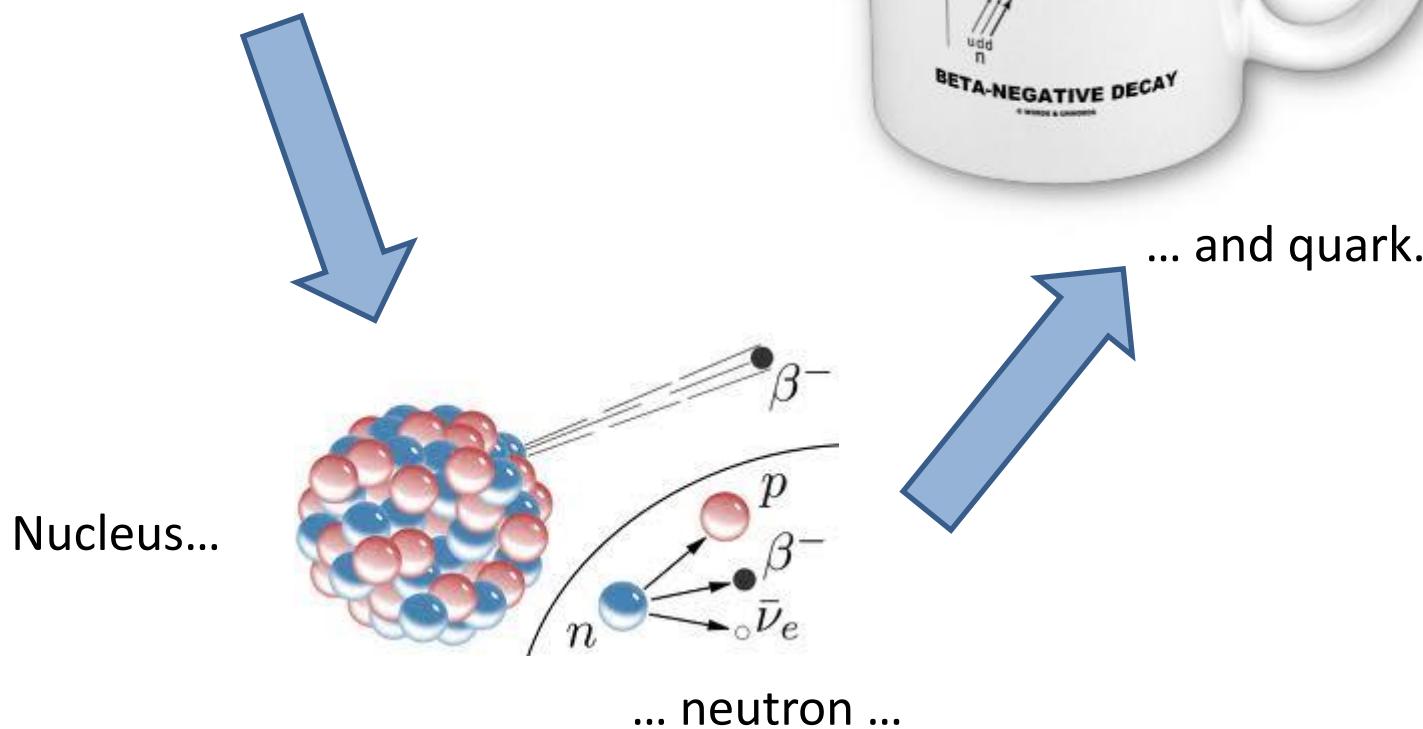
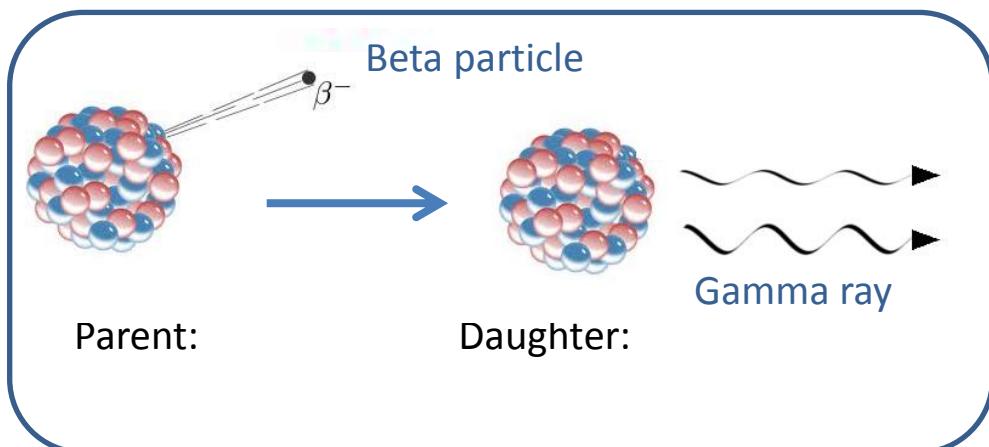


## LTNO : Oriented nuclei

- To probe weak interaction
- To probe nuclear structure
- (To probe solid state )

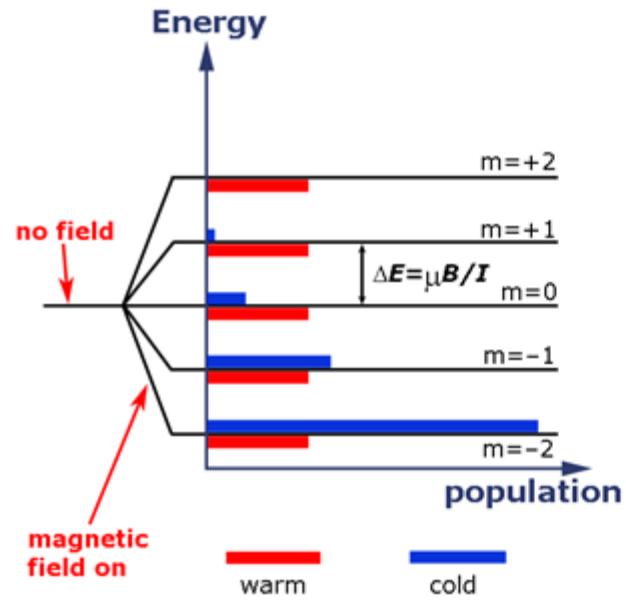


# Beta decay



## Low Temperature Nuclear Orientation

How one can polarize a nucleus?



### LTNO in numbers

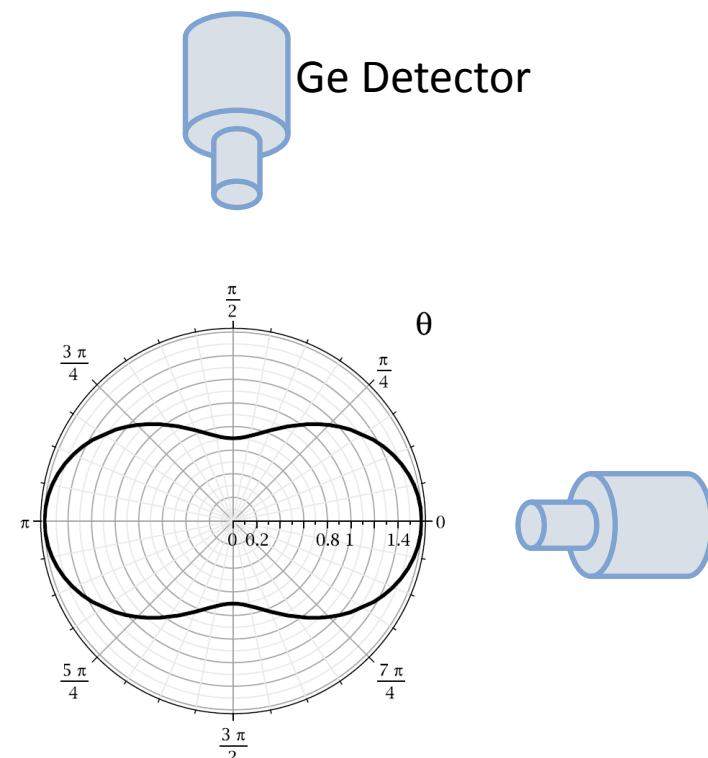
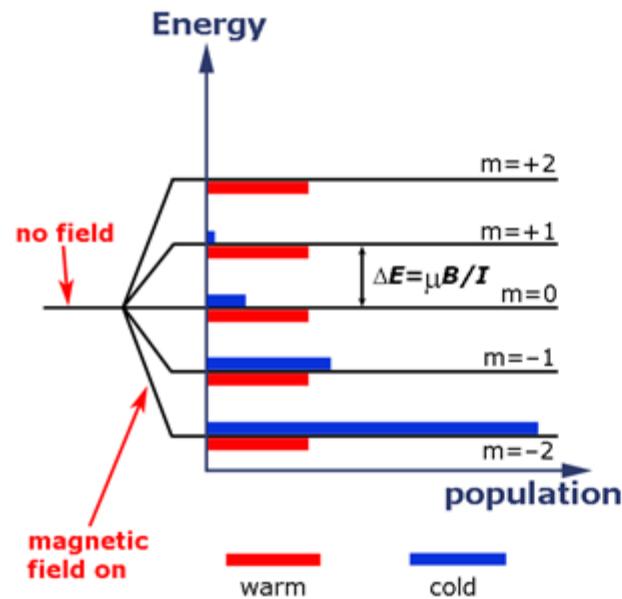
$$B_{\text{ext}} \sim 1 - 2 \text{ T}$$

$$B_{\text{tot}} \sim 10-100 \text{ T}$$

$$T \sim 7-20 \text{ mK}$$

## Low Temperature Nuclear Orientation

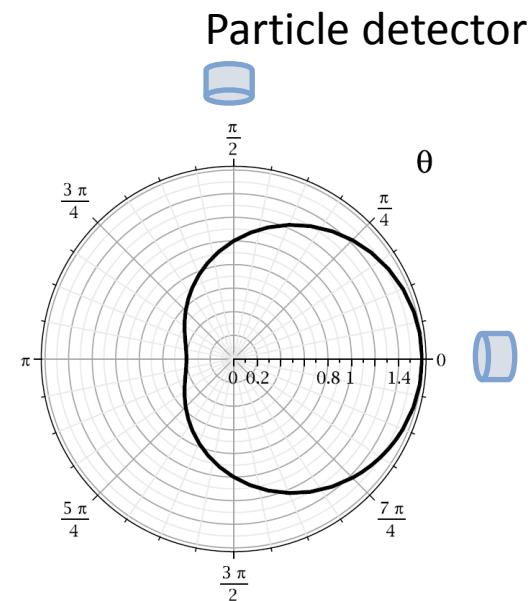
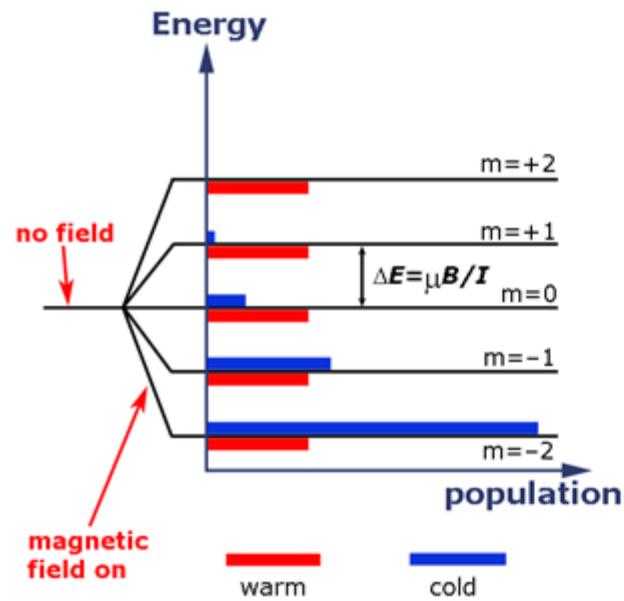
How one can polarize a nucleus?



The detail of the shape of the angular distribution depends on the particular transition: **spins** of the nuclear states involved, **transition multipolarities**, **parity admixture** and also on the environment of the nuclei like the **total magnetic field** and the **temperature**.

## Low Temperature Nuclear Orientation

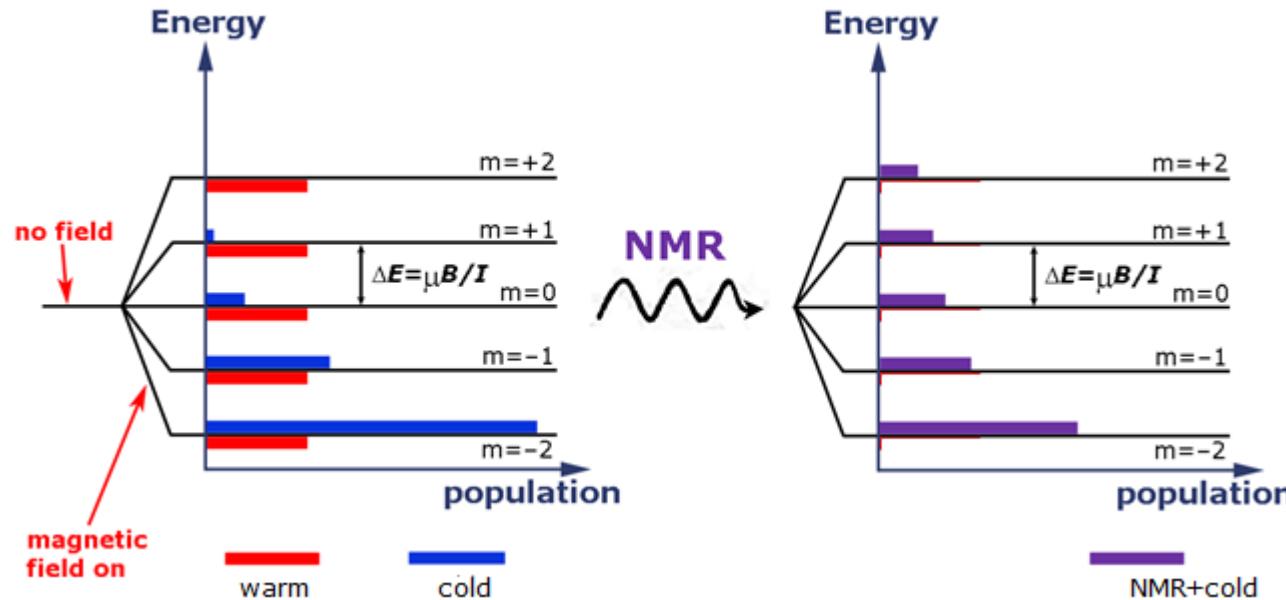
How one can polarize a nucleus?



The detail of the shape of the angular distribution depends on the particular transition: **spins** of the nuclear states involved, **transition multipolarities**, **parity admixture** and also on the environment of the nuclei like the **total magnetic field** and the **temperature**.

## Low Temperature Nuclear Orientation AND Nuclear Magnetic Resonance

How one can play with the nucleus spin?



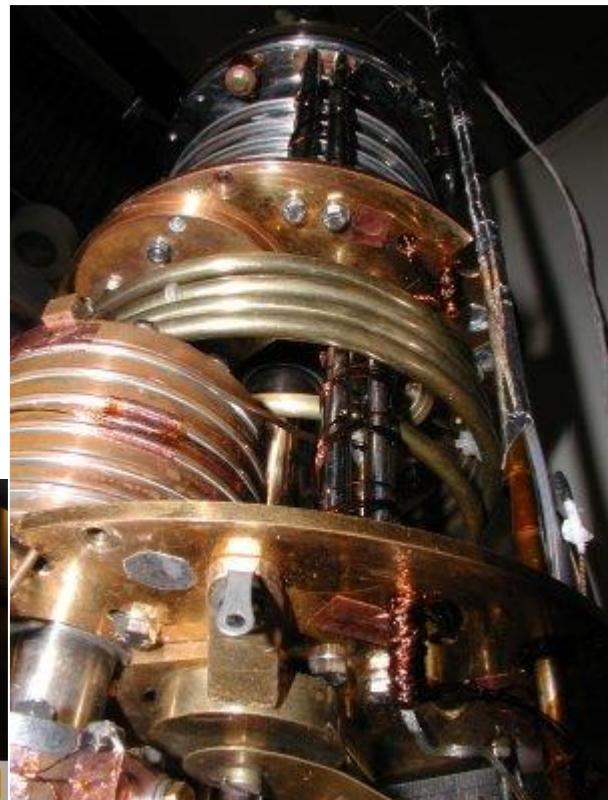
The **good frequency**  $\rightarrow$  the **magnetic moment**

Providing that you know the **magnetic field** and the **temperature**

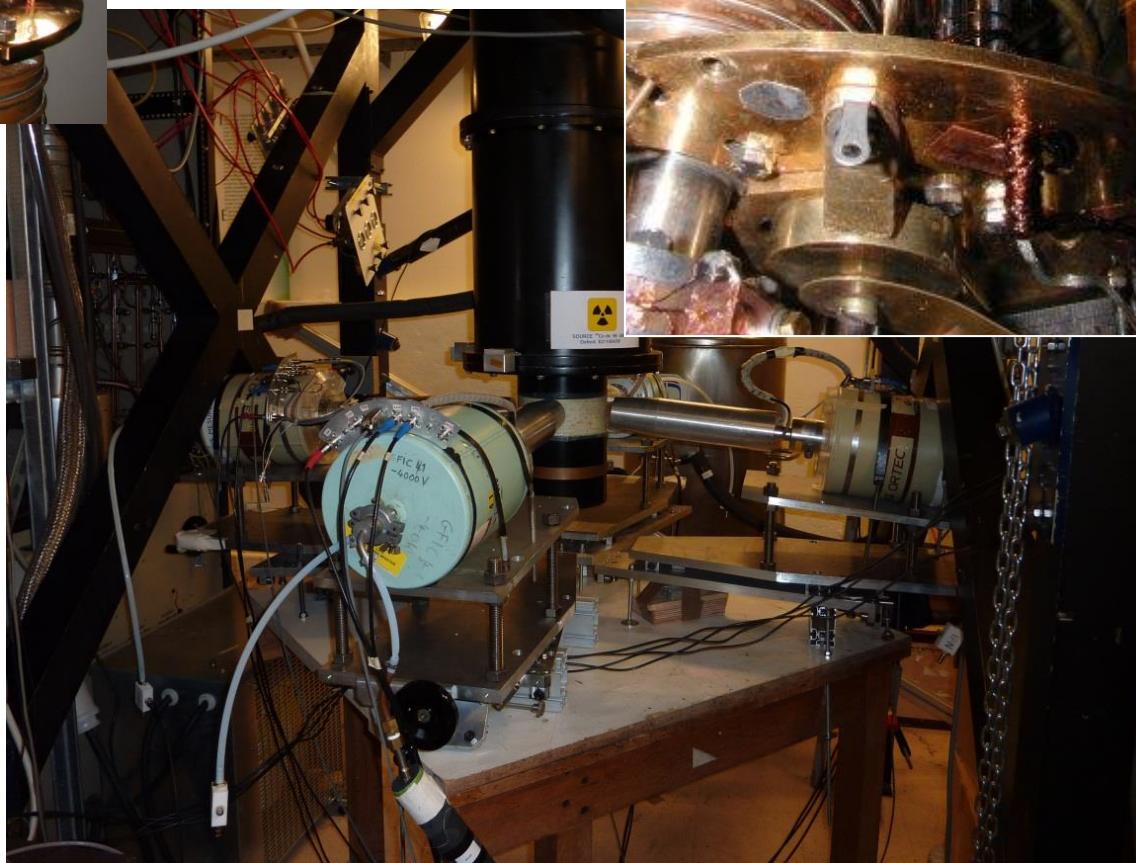
- Hyperfine information
- Nuclear thermometer



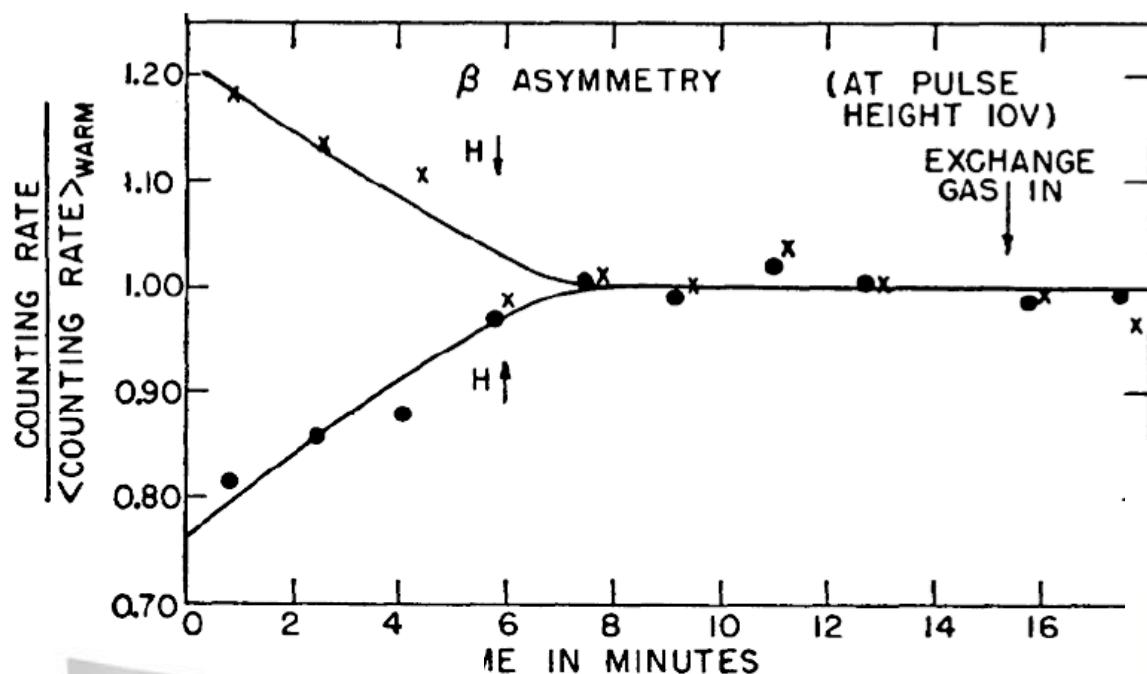
A dilution cryostat ...



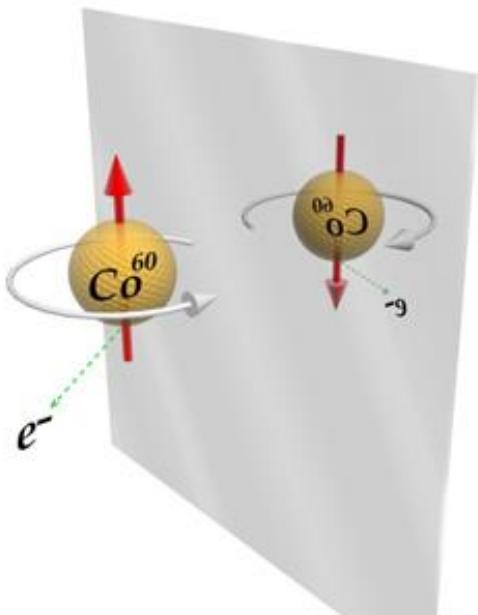
... and a detection system



# Weak interaction tests



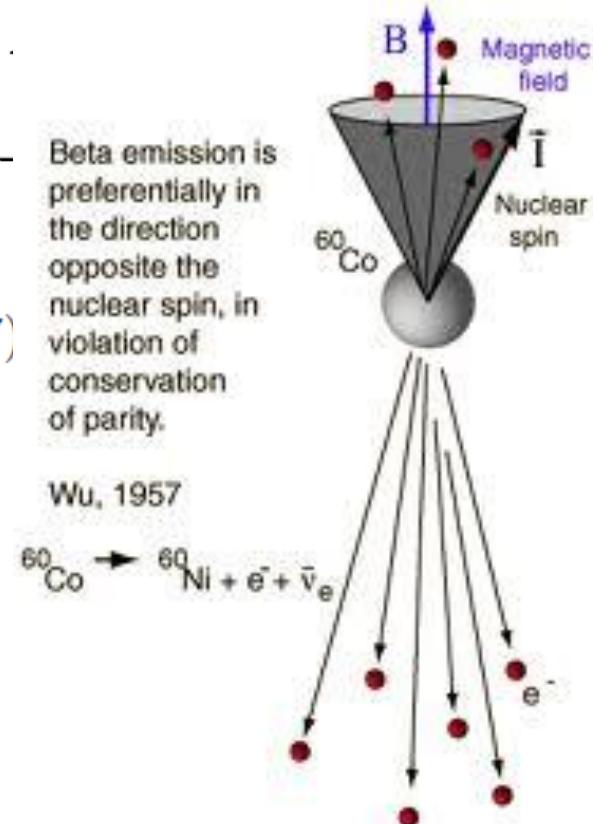
Phys. Rev. 105, 1413 (1957)



C.S. Wu: parity violation in weak interaction

Beta emission is preferentially in the direction opposite the nuclear spin, in violation of conservation of parity.

Wu, 1957



# Weak interaction tests

## Precision measurements of the $^{60}\text{Co}$ $\beta$ -asymmetry parameter in search for tensor currents in weak interactions

F. Wauters,<sup>1,\*</sup> I. Kraev,<sup>1</sup> D. Zákoucký,<sup>2</sup> M. Beck,<sup>1,†</sup> M. Breitenfeldt,<sup>1</sup> V. De Leebeeck,<sup>1</sup> V. V. Golovko,<sup>1,‡</sup> V. Yu. Kozlov,<sup>1</sup> T. Phalet,<sup>1</sup> S. Roccia,<sup>1</sup> G. Soti,<sup>1</sup> M. Tandecki,<sup>1</sup> I. S. Towner,<sup>3</sup> E. Traykov,<sup>1</sup> S. Van Gorp,<sup>1</sup> and N. Severijns<sup>1</sup>

<sup>1</sup>*K. U. Leuven, Instituut voor Kern- en Stralingsfysica,  
Celestijnlaan 200D, B-3001 Leuven, Belgium*

<sup>2</sup>*Nuclear Physics Institute, ASCR, 250 68 Řež, Czech Republic*

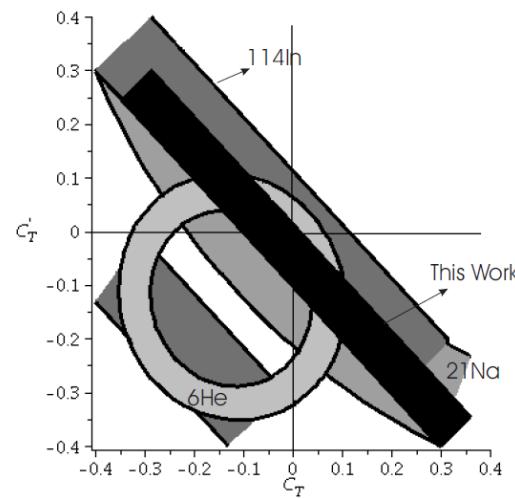
<sup>3</sup>*Cyclotron Institute, Texas A & M University, College Station, Texas 77845, U.S.A.*

(Dated: May 28, 2010)

The  $\beta$ -asymmetry parameter  $\tilde{A}$  for the Gamow-Teller decay of  $^{60}\text{Co}$  was measured by polarizing the radioactive nuclei with the brute force low-temperature nuclear-orientation method. The  $^{60}\text{Co}$  activity was cooled down to milliKelvin temperatures in a  $^3\text{He}$ - $^4\text{He}$  dilution refrigerator in an external 13 T magnetic field. The  $\beta^-$  particles were observed by a 500  $\mu\text{m}$  thick Si PIN diode operating at a temperature of about 10 K in a magnetic field of 0.6 T. Extensive GEANT4 Monte-Carlo simulations were performed to gain control over the systematic effects. Our result,  $A = -1.014(12)_{\text{stat}}(16)_{\text{syst}}$ , is in agreement with the Standard-Model value of  $-0.987(9)$ , which includes recoil-order corrections that were addressed for the first time for this isotope. Further, it enables limits to be placed on possible tensor-type charged weak currents as well as other physics beyond the Standard Model.

$$W(\theta) \propto \left[ 1 + b \frac{m}{E_e} + \frac{\mathbf{p}}{E_e} \cdot \mathbf{AJ} \right]$$

$$\tilde{A}_{\text{exp}} = A_{\text{SM}} + \frac{\gamma m}{E_e} \Re \left( \frac{C_T + C'_T}{C_A} \right)$$



Limited by systematic effects (waiting for a new good idea)

# Weak interaction tests

## Search for CPT violation in the weak interaction

An effective model ...

$$\frac{d\Gamma}{\Gamma_0} = 1 + \vec{\beta} \cdot \left[ A \frac{\langle \vec{I} \rangle}{I} + \xi_1 \hat{n}_1 \right] + \xi_2 \frac{\langle \vec{I} \rangle}{I} \cdot \hat{n}_2.$$

$$\begin{aligned} dW = & \frac{1}{(2\pi)^5} d^3 p d^3 k \delta(E_e + E_\nu - E_0) F(E_e, \pm Z) \xi \\ & \times \left\{ \left( 1 \mp \frac{\mathbf{p} \cdot \hat{s}_e}{E_e} \right) \left[ \frac{1}{2} \left( 1 + B \frac{\mathbf{k} \cdot \hat{\mathbf{l}}}{E_\nu} \right) + t + \frac{\mathbf{w}_1 \cdot \mathbf{k}}{E_\nu} + \mathbf{w}_2 \cdot \hat{\mathbf{l}} + T_1^{km} \hat{\mathbf{l}}^k \hat{\mathbf{l}}^m + \frac{T_2^{kj} \hat{\mathbf{l}}^k k^j}{E_\nu} + \frac{S_1^{kmj} \hat{\mathbf{l}}^k \hat{\mathbf{l}}^m k^j}{E_\nu} \right] \right. \right. \\ & \quad + \left( \left( 1 \mp \frac{(E_e - \gamma m_e)(\mathbf{p} \cdot \hat{s}_e)}{E_e^2 - m_e^2} \right) \frac{p^l}{E_e} \mp \frac{\gamma m_e}{E_e} s_e^l \mp \frac{m_e}{E_e} \sqrt{1 - \gamma^2} (\hat{\mathbf{p}} \times \hat{s}_e)^l \right) \\ & \left. \times \left[ \frac{1}{2} \left( A - 3c \frac{\mathbf{k} \cdot \hat{\mathbf{l}}}{E_\nu} \right) \hat{\mathbf{l}}^l + \frac{1}{2}(a+c) \frac{k^l}{E_\nu} + w_3^l + \frac{T_3^{lj} k^j}{E_\nu} + T_4^{lk} \hat{\mathbf{l}}^k + S_2^{lmk} \hat{\mathbf{l}}^m \hat{\mathbf{l}}^k + \frac{S_3^{lmj} \hat{\mathbf{l}}^m k^j}{E_\nu} + \frac{R^{lmkj} \hat{\mathbf{l}}^m \hat{\mathbf{l}}^k k^j}{E_\nu} \right] \right\}, \end{aligned}$$

... based on a theoretical framework

LTNO: large polarization (up to 80%)

Timeline:

- reanalysis of existing data (thesis of F. Wauters KULeuven)
- New data with  ${}^{60}\text{Co}$  (Off Line)

**Magnetic Dipole Moment of the Doubly-Closed-Shell Plus One Proton Nucleus  $^{49}\text{Sc}$** 

T. Ohtsubo,<sup>1</sup> N. J. Stone,<sup>2,3</sup> J. R. Stone,<sup>2,3</sup> I. S. Towner,<sup>4</sup> C. R. Bingham,<sup>2</sup> C. Gaulard,<sup>5</sup> U. Köster,<sup>6</sup> S. Muto,<sup>7</sup> J. Nikolov,<sup>8</sup> K. Nishimura,<sup>9</sup> G. S. Simpson,<sup>10</sup> G. Sotí,<sup>11</sup> M. Vesovic,<sup>8</sup> W. B. Walters,<sup>12</sup> and F. Wauters<sup>11</sup>

$$|\mu|(^{49}\text{Sc}, 7/2^-, \text{g.s.}) = 5.616(25) \mu_N.$$

A single  $f_{7/2}$  proton outside doubly magic  $^{48}\text{Ca}$  ( $Z=20$ ,  $N=28$ )

Good test for fundamental theory of nuclear magnetism

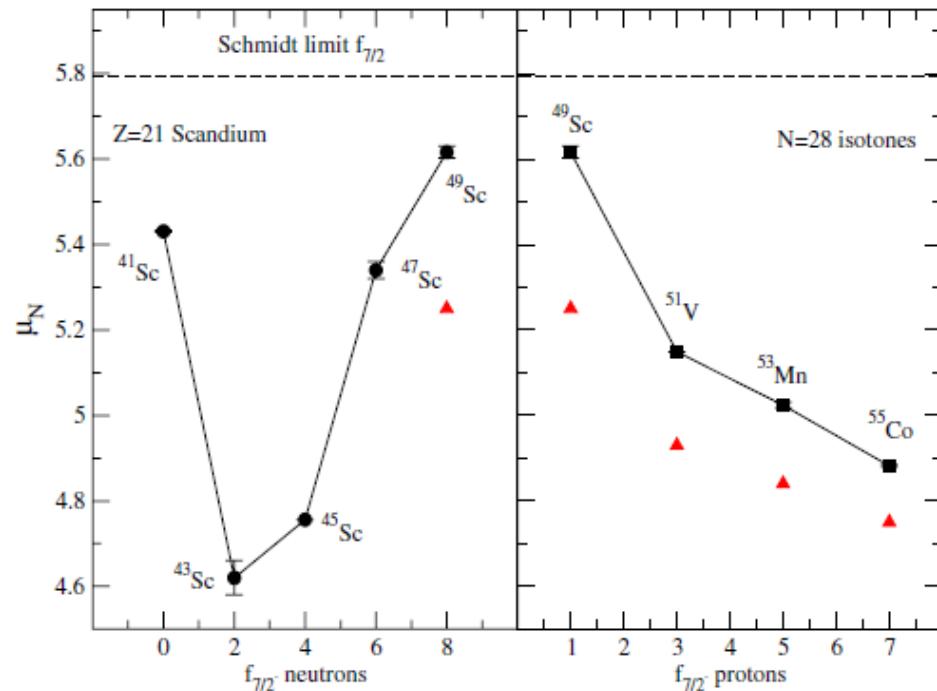


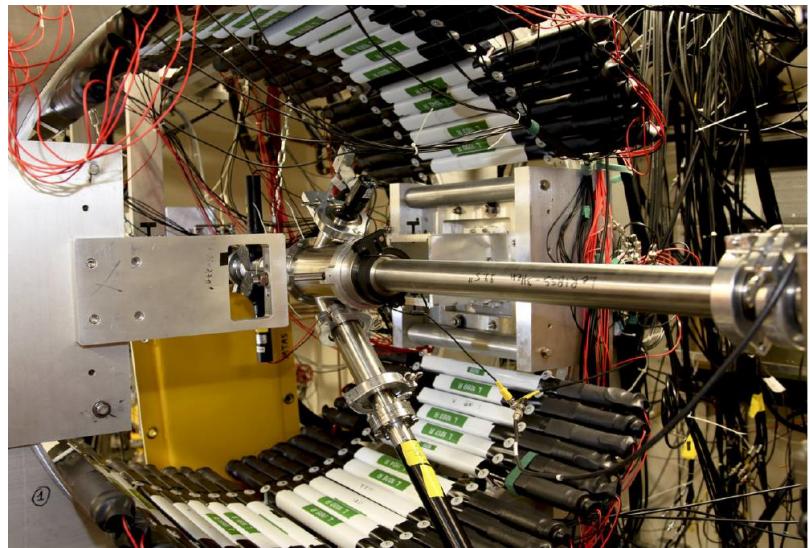
TABLE III. Theoretical and experimental magnetic moments of Sc and Cu isotopes with closed subshell neutron configurations. All entries for moments are in  $\mu_N$ .

$Z$	$N$	Configuration	Schmidt	Theory	Experiment	References		
$^{41}\text{Sc}$	21	$20$	$\pi(f_{7/2})^1$	$\nu(f_{7/2})^0$	+5.794	+5.697	+5.431(2)	[4,13]
$^{49}\text{Sc}$	21	$28$	$\pi(f_{7/2})^1$	$\nu(f_{7/2})^8$	+5.794	+5.583	+5.616(25)	This work
$^{57}\text{Cu}$	29	$28$	$\pi(p_{3/2})^1$	$\nu(f_{7/2})^8$	+3.794	+2.404	+2.582(7)	[15]
$^{69}\text{Cu}$	29	$40$	$\pi(p_{3/2})^1$	$\nu(f_{5/2})^6$	+3.794	+2.874	+2.84(1)	[14,16]

## Beta-delayed neutrons from oriented $^{137,139}\text{I}$ and $^{87,89}\text{Br}$ nuclei

### VANDLE@NICOLE Versatile Array of Neutron Detectors at Low Energy

First angle and energy resolved beta delayed neutron measurement on medium heavy nuclei.

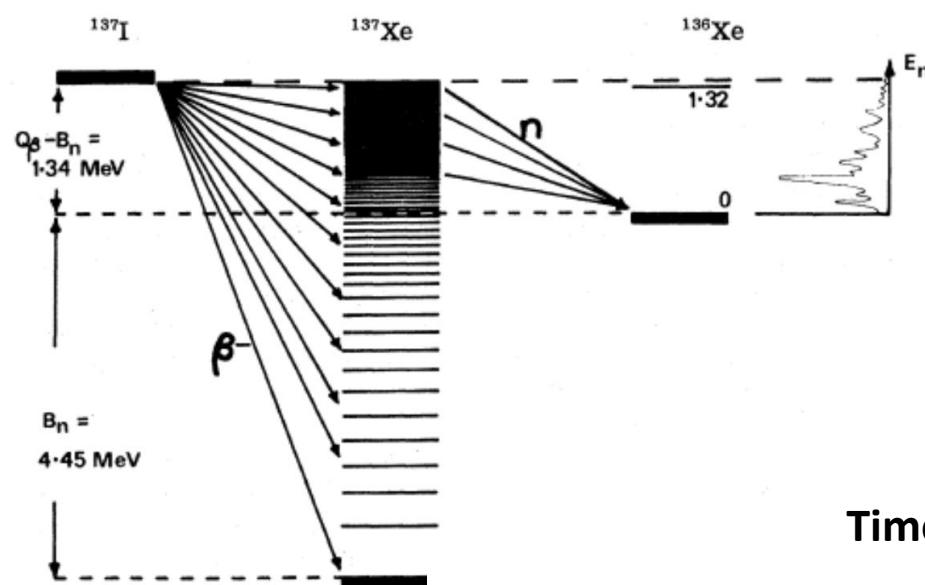


Proposal at the 45<sup>th</sup> INTC  
Spokesperson: R. Grzywacz:

## Beta-delayed neutrons from oriented $^{137,139}\text{I}$ and $^{87,89}\text{Br}$ nuclei

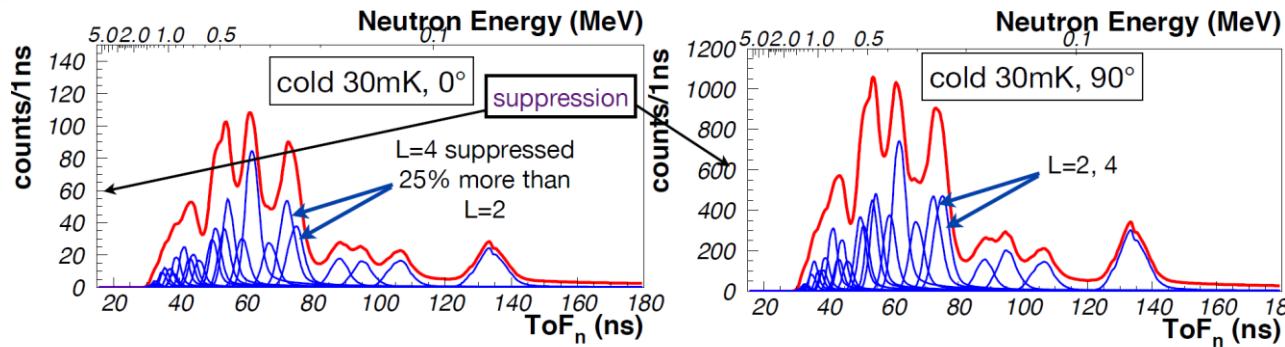
### VANDLE@NICOLE Versatile Array of Neutron Detectors at Low Energy

Precursor      Emitter      Daughter



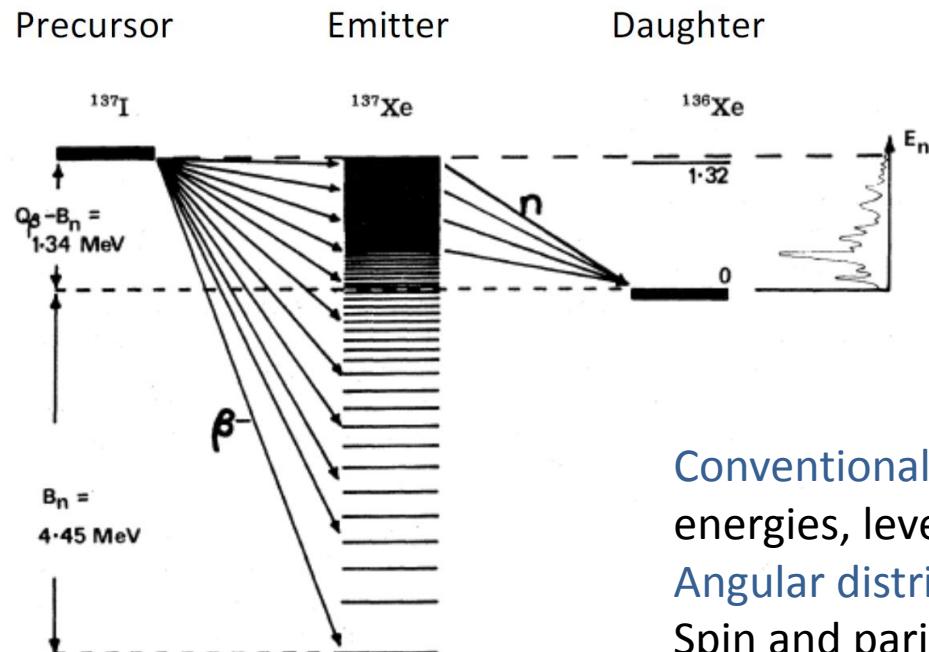
### Time of flight experiment

Theory and simulation ready



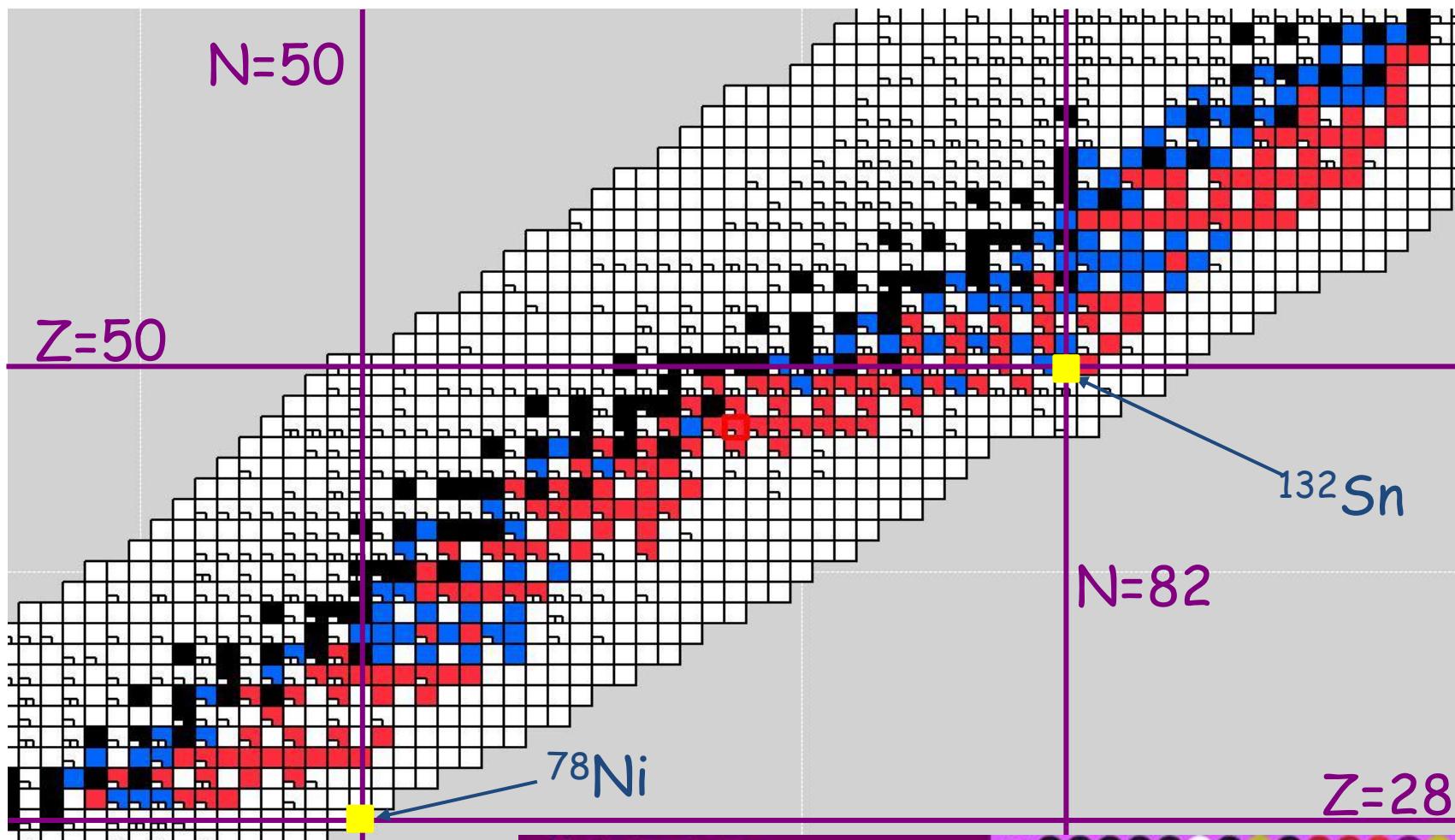
## Beta-delayed neutrons from oriented $^{137,139}\text{I}$ and $^{87,89}\text{Br}$ nuclei

### VANDLE@NICOLE Versatile Array of Neutron Detectors at Low Energy



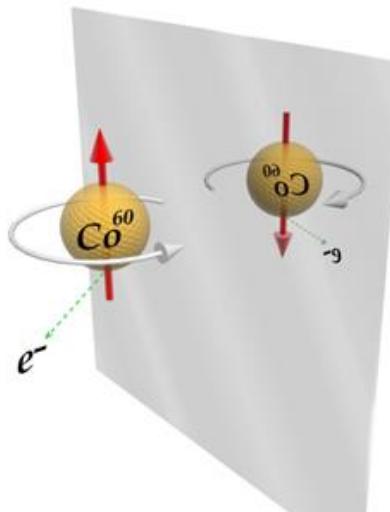
Conventional spectroscopy:  
energies, level structures intensities,  
Angular distribution:  
Spin and parity of the levels  
and the angular momenta (partial waves)

Particle emission: physics at the drip--lines  
r--process nuclei are delayed neutron emitters  
power plant modeling

ON line study: Structure around doubly-magic neutron-rich nuclei :  $^{78}\text{Ni}$  and  $^{132}\text{Sn}$ 

~50 years after the first measurements there is still innovative physics to be done

## Nuclear structure physics

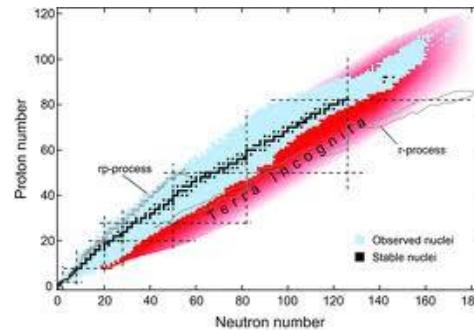


## Solid state physics

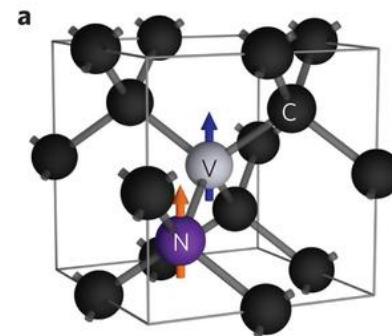
2 On Line systems:

[NICOLE@ISOLDE@CERN](mailto:NICOLE@ISOLDE@CERN)

And soon [POLAREX@ALTO@ORSAY](mailto:POLAREX@ALTO@ORSAY)



## Fundamental study of the weak interaction



## *The collaboration*

**University of Maryland, College Park, USA** J.R. Stone, W. B. Walters  
**ILL Grenoble, FR** U. Köster  
**University of Surrey, Guildford, UK** P. M. Walker  
**McMaster University, Hamilton, CA** B. Singh  
**University of Tennessee , Knoxville, USA** C.R.Bingham, R.Grzywacz, K. Kolos,  
M. Madurga, N.J. Stone  
**Niigata University, Niigata, JP** T. Otsubo  
**University of Novi Sad, Novi Sad, Serbia** M. Veskovic J. Nikolov  
**CSNSM, Orsay, FR** A. Astier, G. Audi, S. Cabaret, A. Etilé, C. Gaulard,  
G. Georgiev, S. Roccia  
**IPNO, Orsay, FR** F. Ibrahim, D. Verney  
**University of Western Scotland, Paisley, UK** G. Simpson  
**INM, Paris, FR** L. Risegari



Nuclear moment measurement  
Past Sc NICOLE@CERN  
Futur Polarex@ALTO

More exotic stuff  
Parity admixture Hf  
Beta delayed neutrons I

ON line study:  $^{137}\text{I}$ 

Measurement of magnetic moment of the odd proton  $7/2^+$  state

Search for strong parity admixture in  $^{137}\text{Xe}$

Anisotropy of  $\beta$ -delayed neutron emission

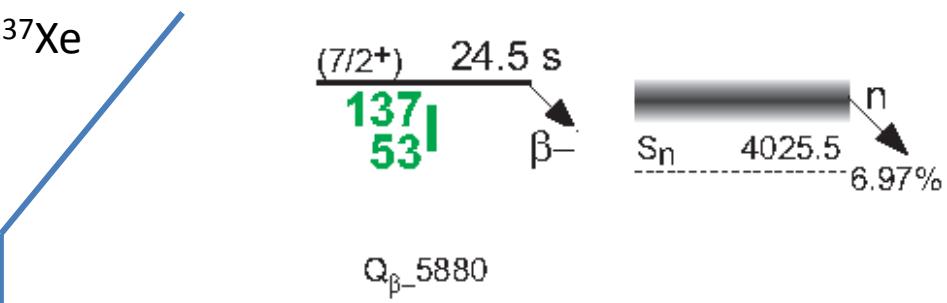
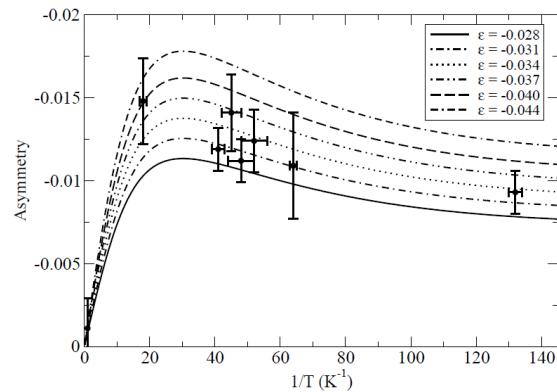
Courtesy N. stone  
(University of Oxford and  
University of Tennessee )

### $\gamma$ -decay of $^{137}\text{Xe}^*$ and $\beta$ -delayed neutron emission from $^{137}\text{Xe}$

Anisotropy of  $\gamma$  emission

High density of  $7/2^+$  and  $7/2^-$  states in  $^{137}\text{Xe}$   
( $7/2^-$  ground state)

Strong parity admixture?



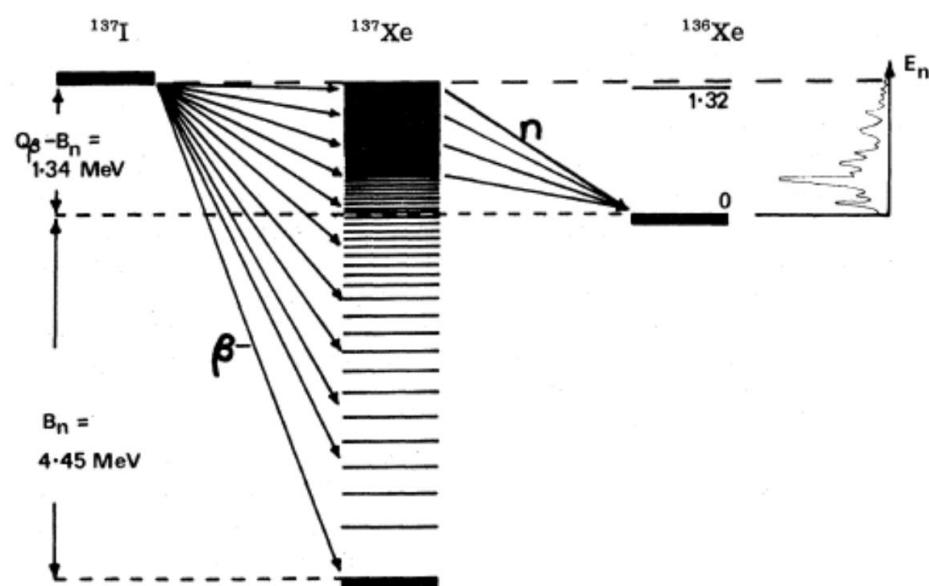
Anisotropy of  $\beta$ -delayed neutron emission  
Access to quantum barrier penetration studies  
Neutron wave function

FIG. 8: Measured asymmetry  $\mathcal{A}$  of the 501 keV transition, as a function of inverse temperature, compared with calculations using Eq. 4 for a range of values of the E2/M2 mixing ratio  $\epsilon$ .

Beta-delayed neutrons from oriented  $^{137}\text{I}$ ,  $^{139}\text{I}$  and  $^{87,89}\text{Br}$  nuclei

## VANDLE@NICOLE Versatile Array of Neutron Detectors at Low Energy

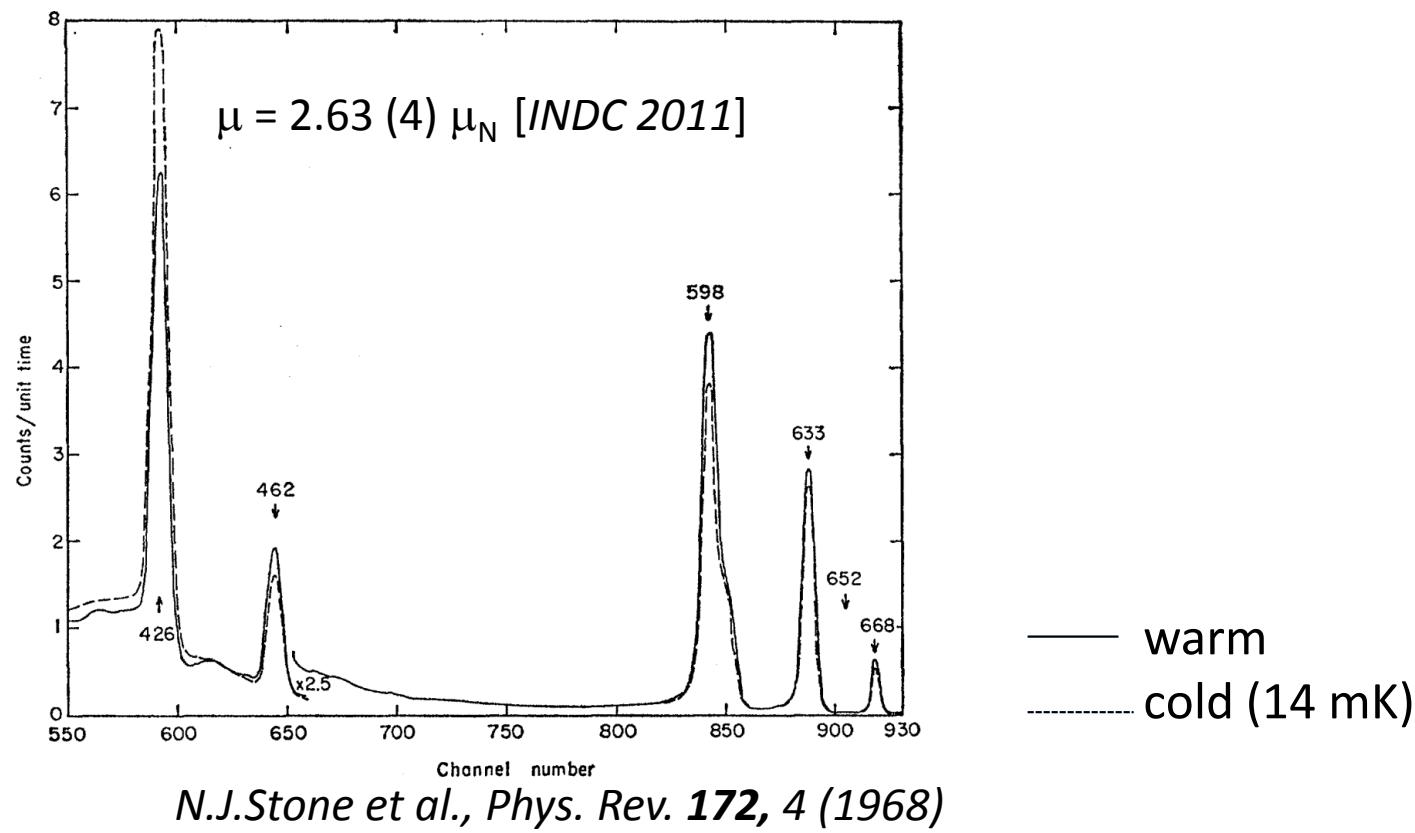
Precursor      Emitter      Daughter



## OFF Line study : 125Sb and 60Co

Ph.D. of A. Etilé

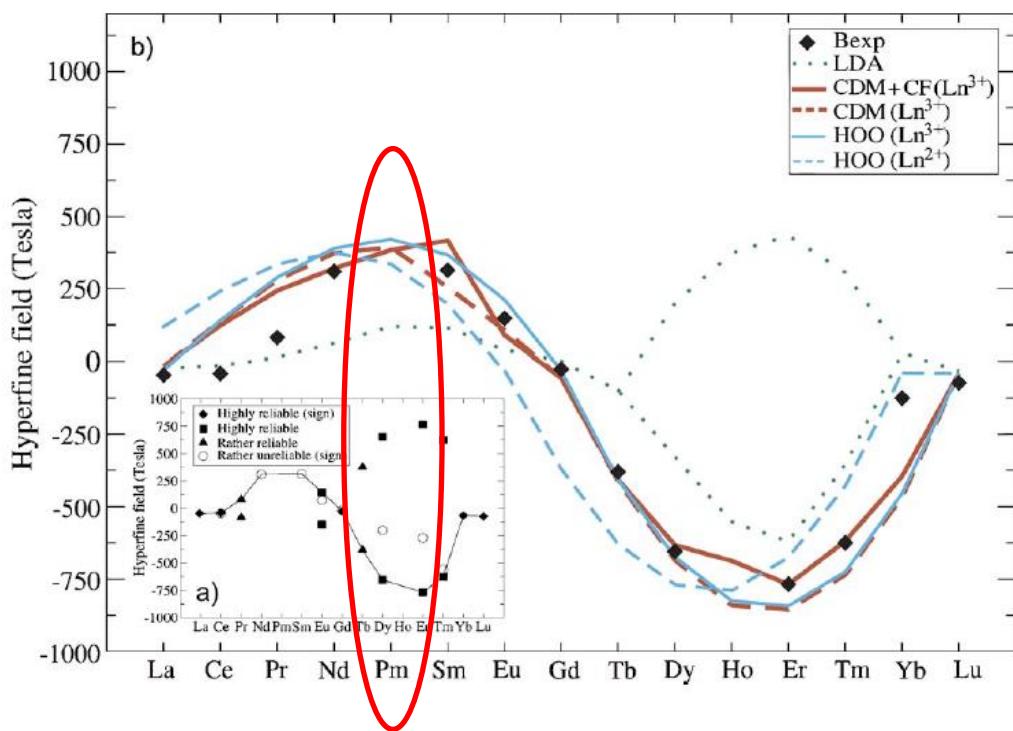
Measurement of the magnetic moment of 125Sb as final commissioning  
Test of CPT in the weak sector



## OFF Line study : 147Pm, 149Pm, 151Pm

Measurement of the hyperfine field at the promethium in iron  
Measurement of the magnetic moment of 149Pm and 151Pm

PHYSICAL REVIEW B 74, 014409 (2006)



Also the value of the hyperfine field  
is needed to measure any Pm  
magnetic moment with LTNO

Need beta detectors

OFF Line study :  $^{77}\text{Ge}$ *Courtesy D. Verney (IPNO)*Measurement of the magnetic moment of  $^{77}\text{Ge}$ Properties of neutron-rich nuclei between  $N = 40$  and  $N = 50$  shell closures $^{77}_{32}\text{Ge}_{45}$  with  $J^\pi = 7/2^+$ 

This level could easily be reproduced by

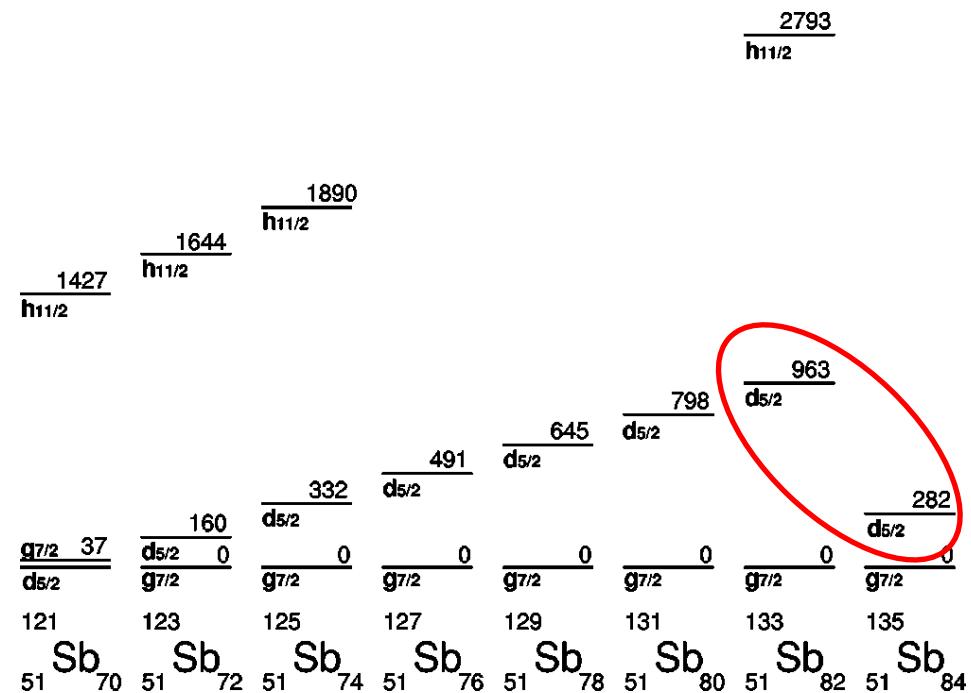
Coriolis-coupling model

or

 $\nu 2d_{5/2}$  contribution to the wave function $\mu$  measurement :  $\mu < 1 \Rightarrow$  Lost of collectivity, no permanent deformation? $\mu \approx 1 \Rightarrow$  Similarity with  $^{79}_{34}\text{Se}_{45}$  ? $\mu \approx |\mu_n| \Rightarrow$  Coriolis mixing ?This measurement will allow the first direct evidence of the stability  
of deformation enhanced by  $Z=32$  effect

ON line study:  $^{134}\text{Sb}^*$ ,  $^{136}\text{I}^*$ ,  $^{137}\text{I}^*$ Courtesy G. Simpson  
(LPSC)

Measurement of magnetic moment of isomeric states

Magnetic properties of nuclei close to  $^{132}_{50}\text{Sn}_{82}$  to test neutron-proton interactions in shell-model calculations

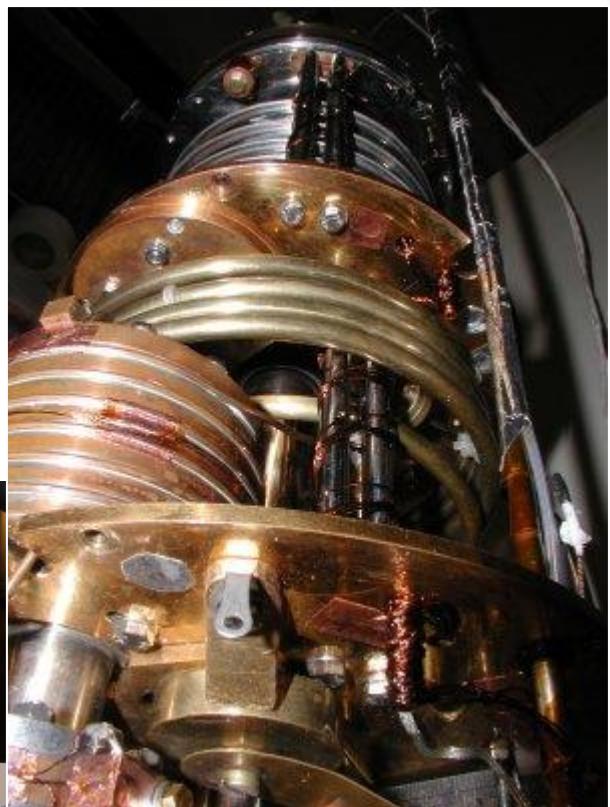
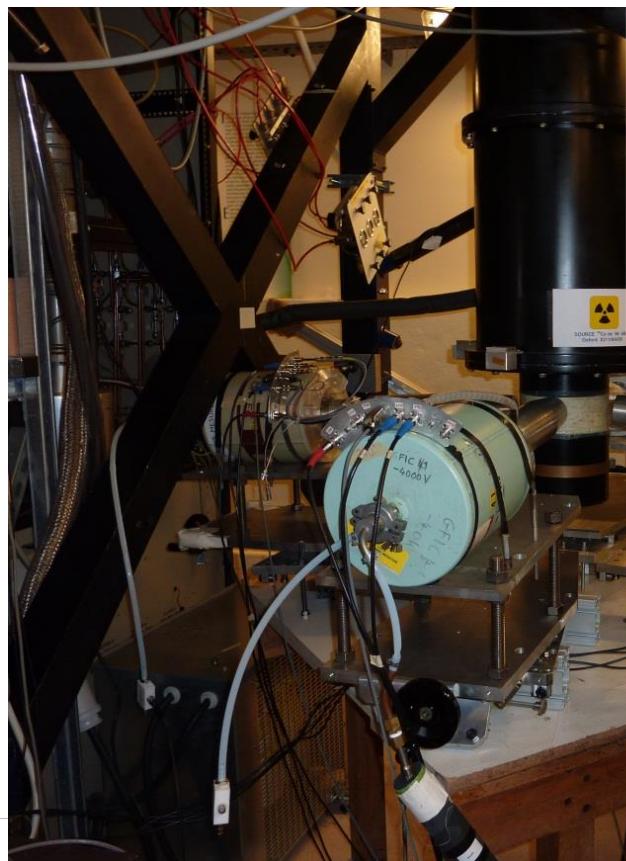
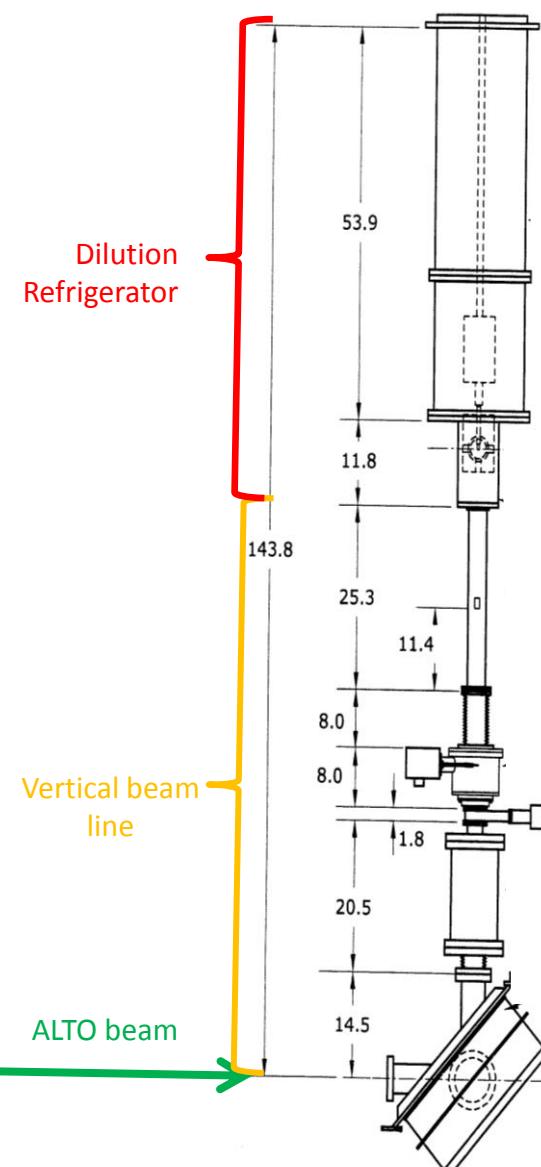
Shell-model calculations unable to reproduce this drop

 $\mu$  measurements of  $^{134}\text{Sb}^*$ ,  $^{136}\text{I}^*$ ,  $^{137}\text{I}^*$ 

Level systematics of the neutron-rich odd-mass Sb isotopes

J. Shergur *et al.*, Phys. Rev. C65, 034313 (2002)Energy of the  $\pi\text{d}_{5/2}$  orbit drops unexpectedly for Sb (N=82) and I (N=82)





## PolarEx

Renovation of the dilution cryostat

Thermometry

Electronics

Acquisition control



## Preparation on the ALTO site

Structure and platforms

Beam design

## R&D

New beta detectors

## *L'orientation nucléaire*

Pourquoi ?

- Pour jouer avec les spins
- Pour créer une direction privilégiée dans l'univers et étudier les symétries

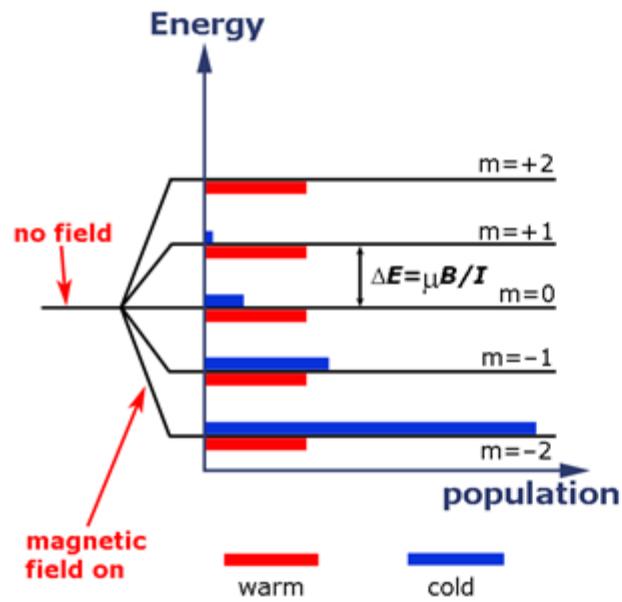
Comment ?

- En créant une direction privilégiée dans le milieu

PolarEx



## Comment orienter un noyau ?



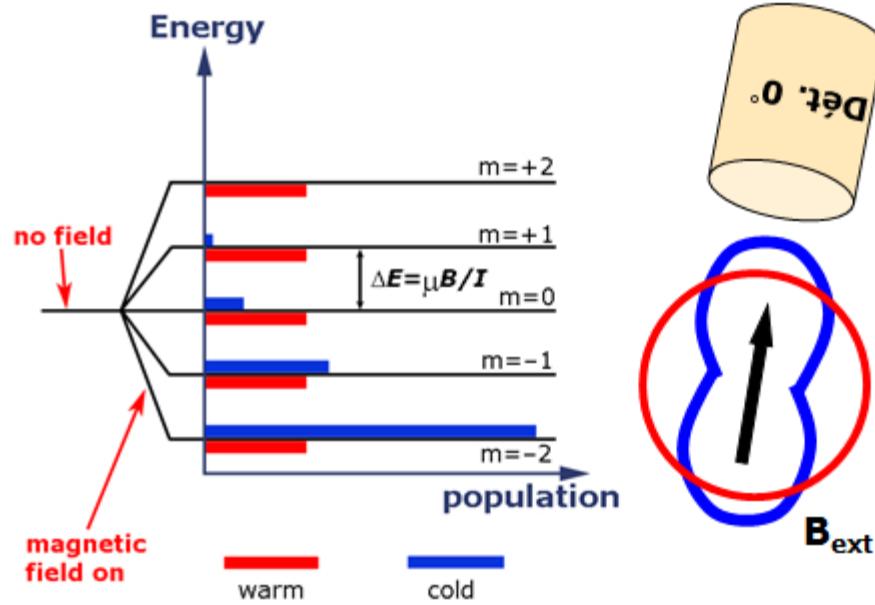
Polarex en nombre

$$B_{\text{ext}} = 0.5 \text{ T}$$

$$B_{\text{tot}} = 10-100 \text{ T}$$

$$T = 7-20 \text{ mK}$$

## Comment orienter un noyau ?



*Comment observer  
l'orientation d'un noyau?*

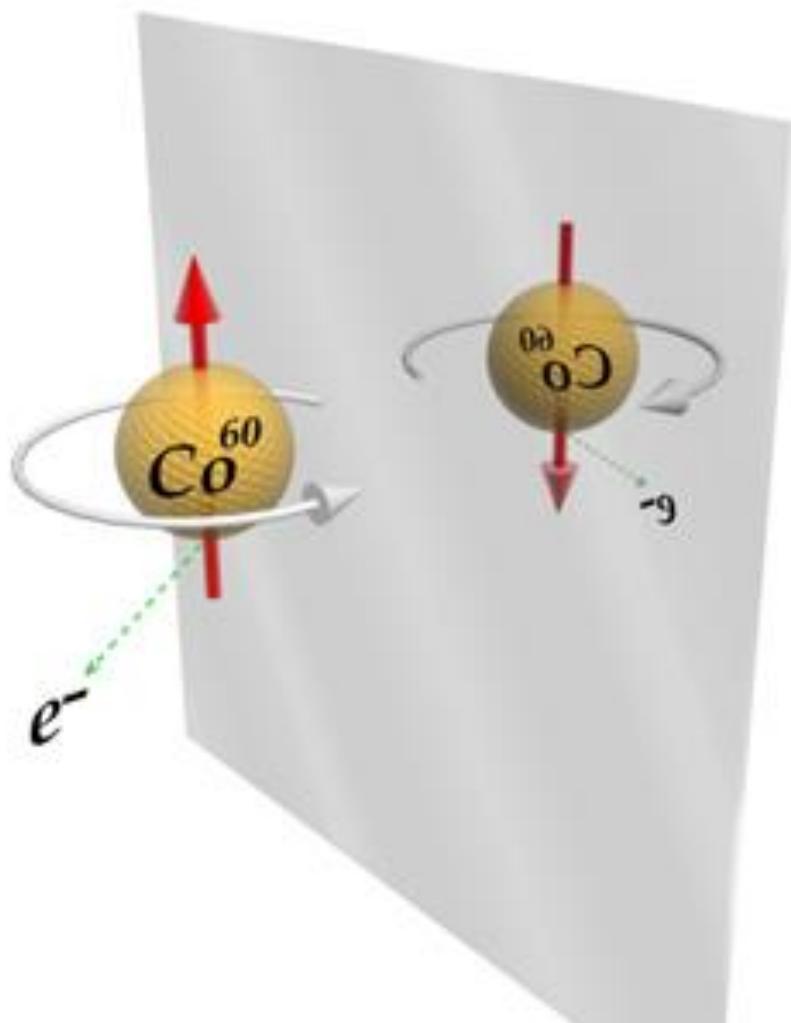


Polarex en nombre

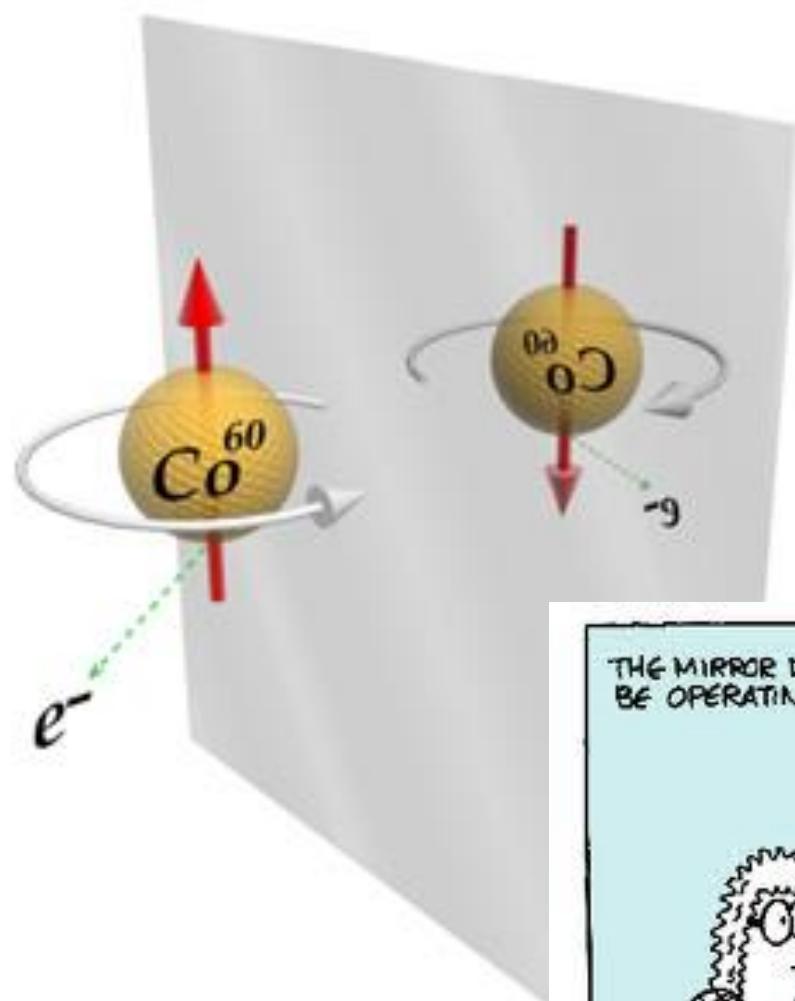
$$B_{\text{ext}} = 0.5 \text{ T}$$

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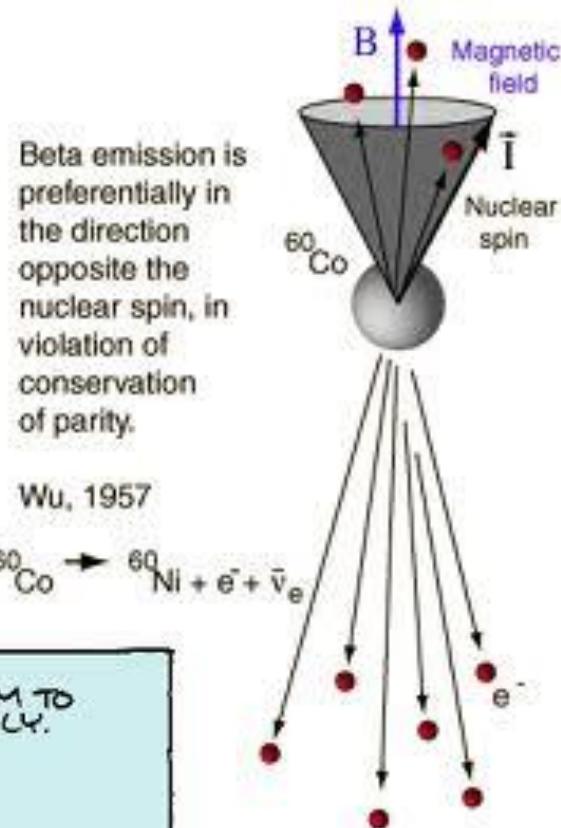
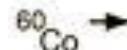


Et la parité dans tout cela ?

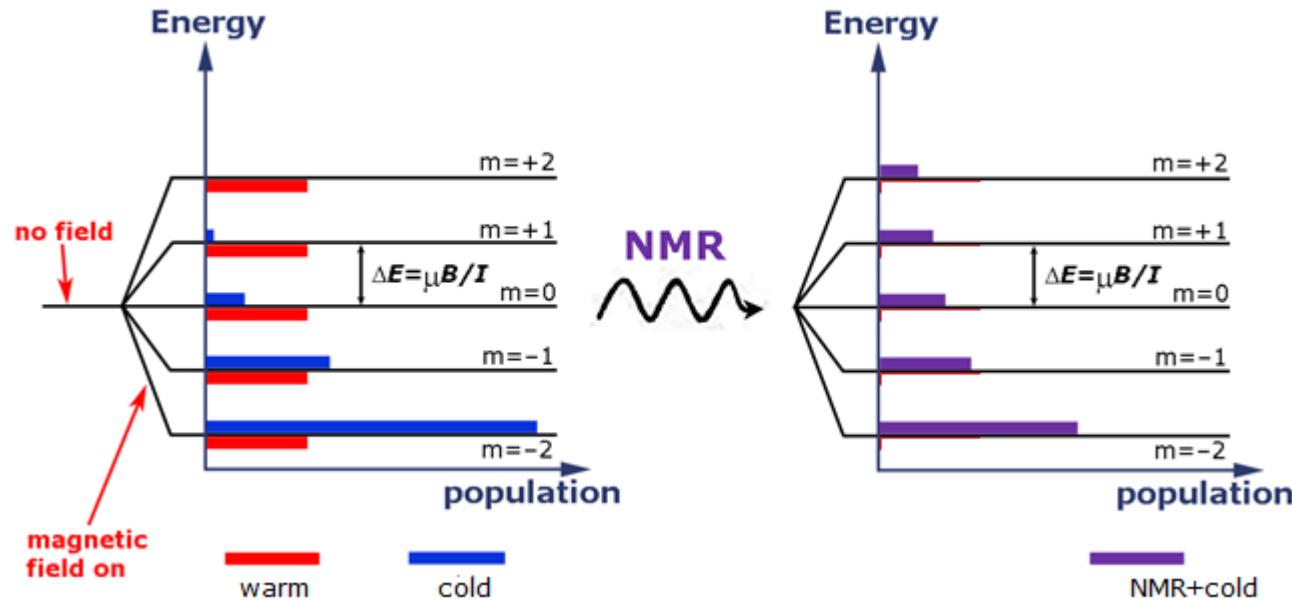


Beta emission is preferentially in the direction opposite the nuclear spin, in violation of conservation of parity.

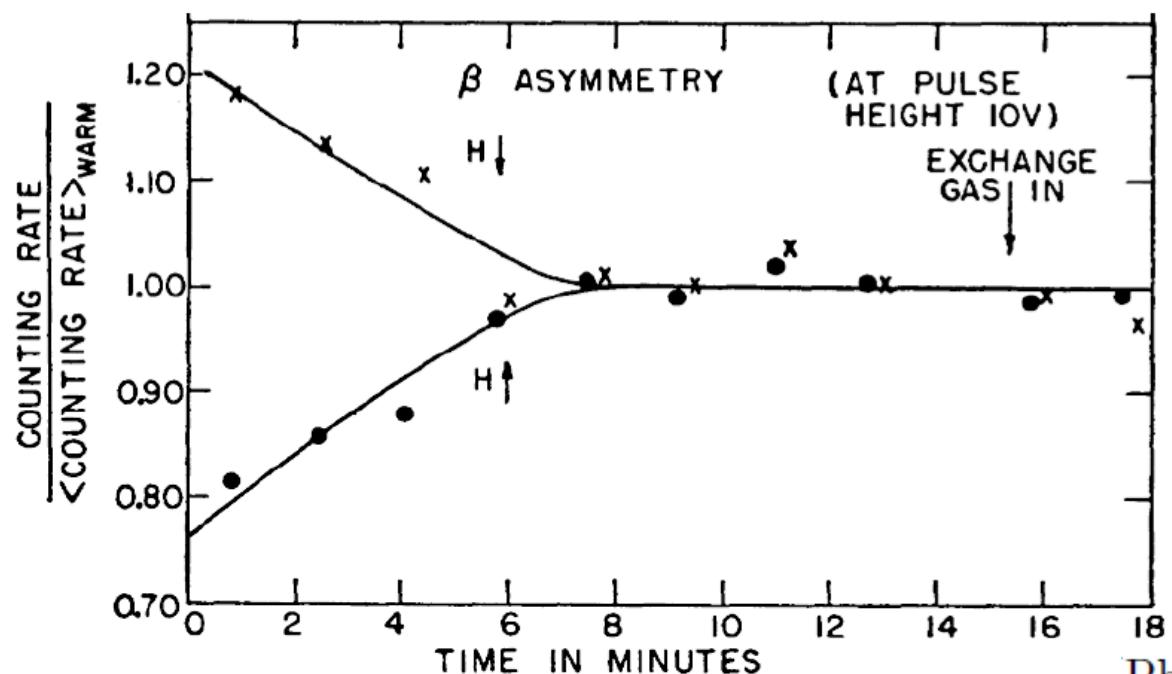
Wu, 1957



## Comment jouer avec le spin du noyau ?

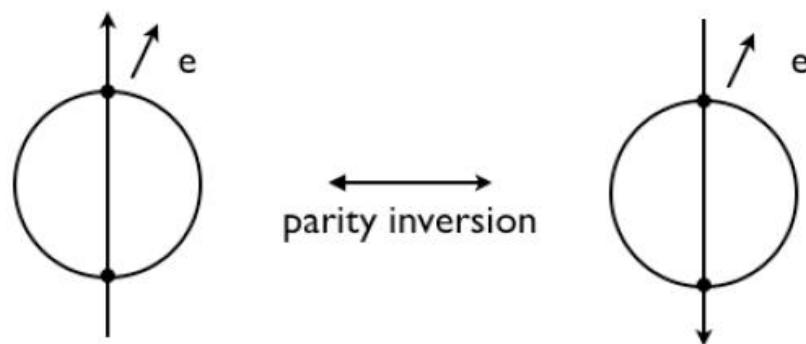


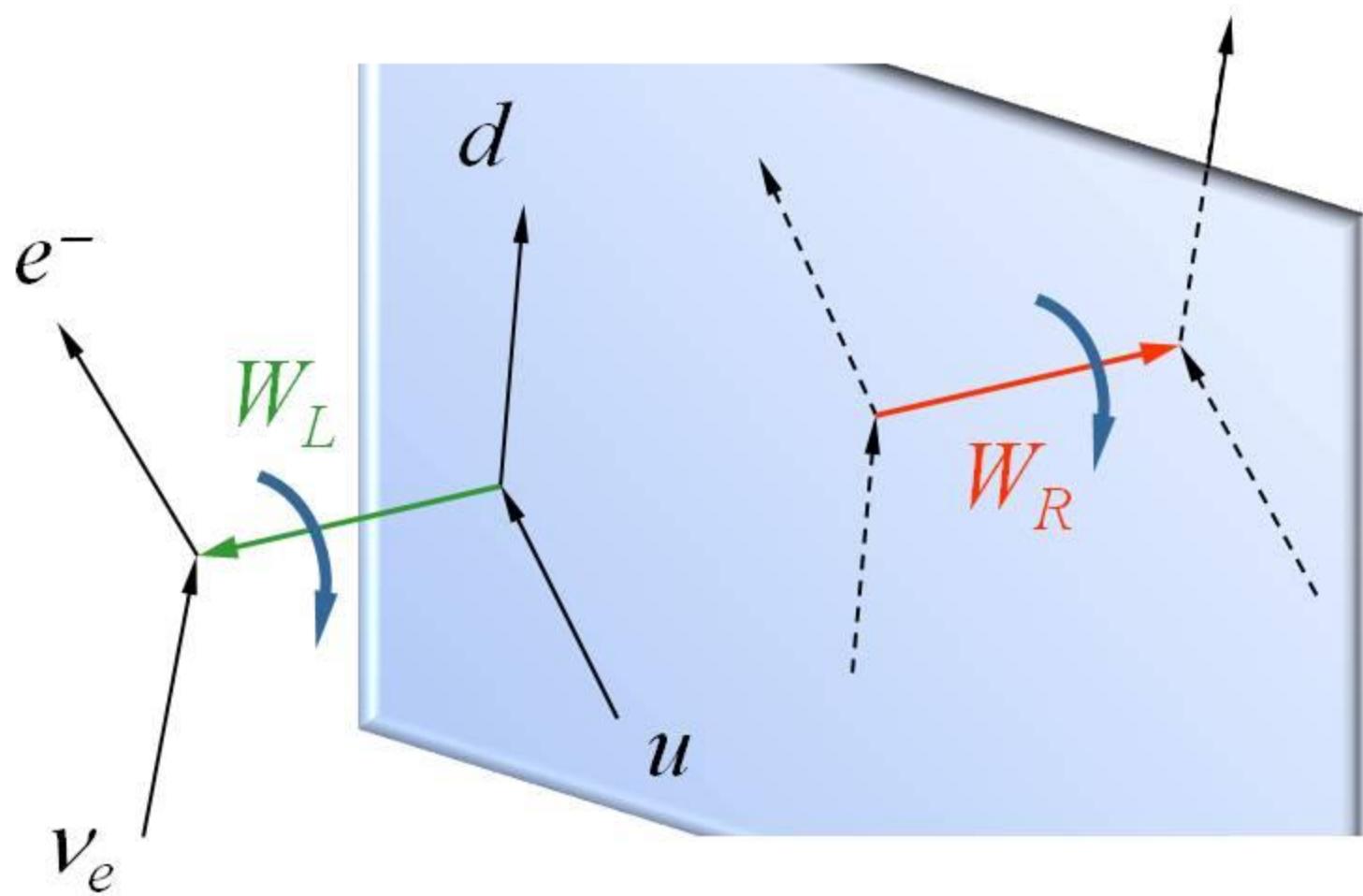
La bonne fréquence -> le moment magnétique



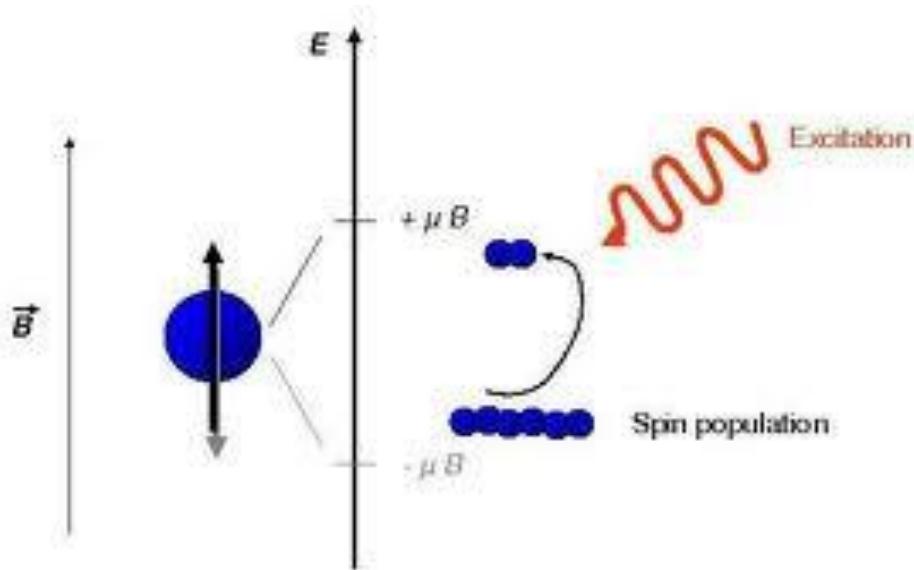
C.S. Wu: parity violation in weak interaction

Phys. Rev. 105, 1413 (1957)





## Comment jouer avec le spin du noyau ?



La **bonne fréquence** -> le **moment magnétique**

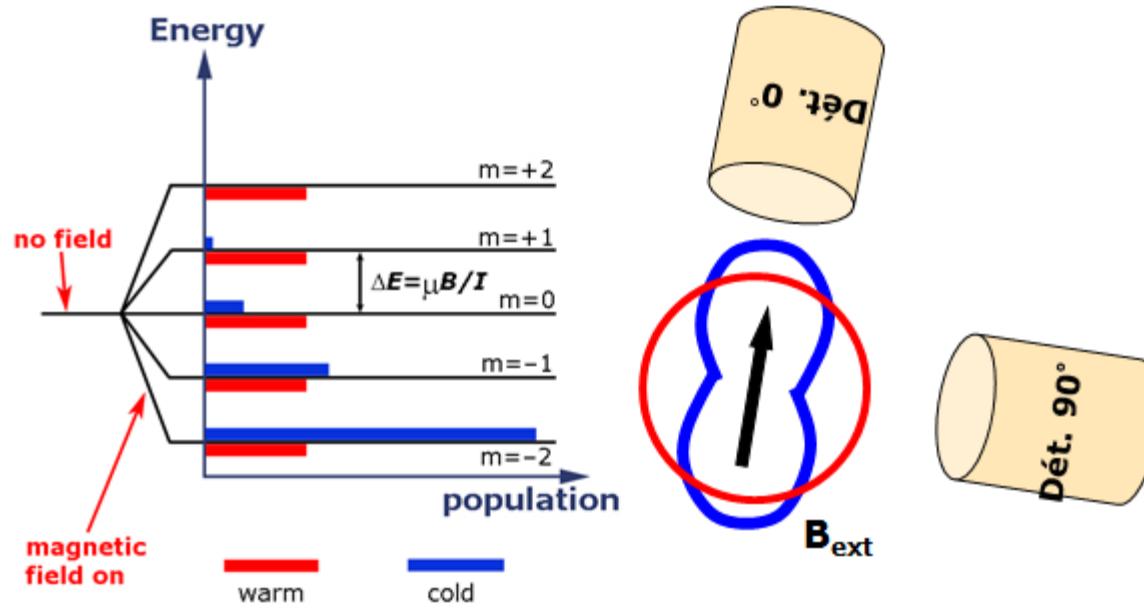
Si on connaît par ailleurs **le champ magnétique** et la **température**

- Structure hyperfine
- Thermomètre nucléaire



T. D. Lee et C. N. Yang

How one can polarize a nucleus?



### Polarex in numbers

$$B_{\text{ext}} = 1.5 \text{ T}$$

$$B_{\text{tot}} = 10-100 \text{ T}$$

$$T = 7-20 \text{ mK}$$