The weak interaction and parity violation in atomic physics

Claude Bouchiat memorial session

ENS Summer Institute

Paris, July 13th 2023

Mark Plimmer

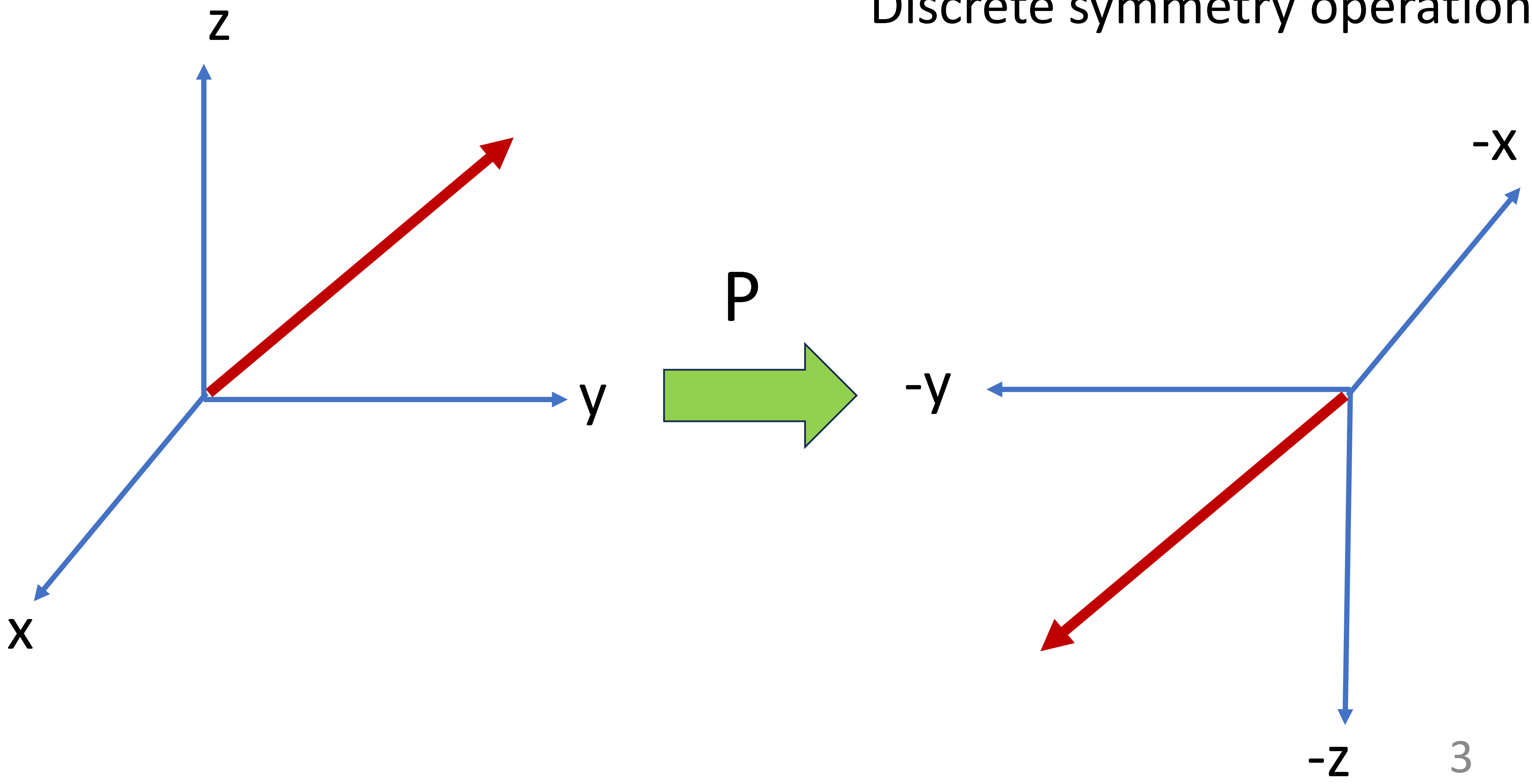
Conservatoire national des arts et métiers, Paris

Outline

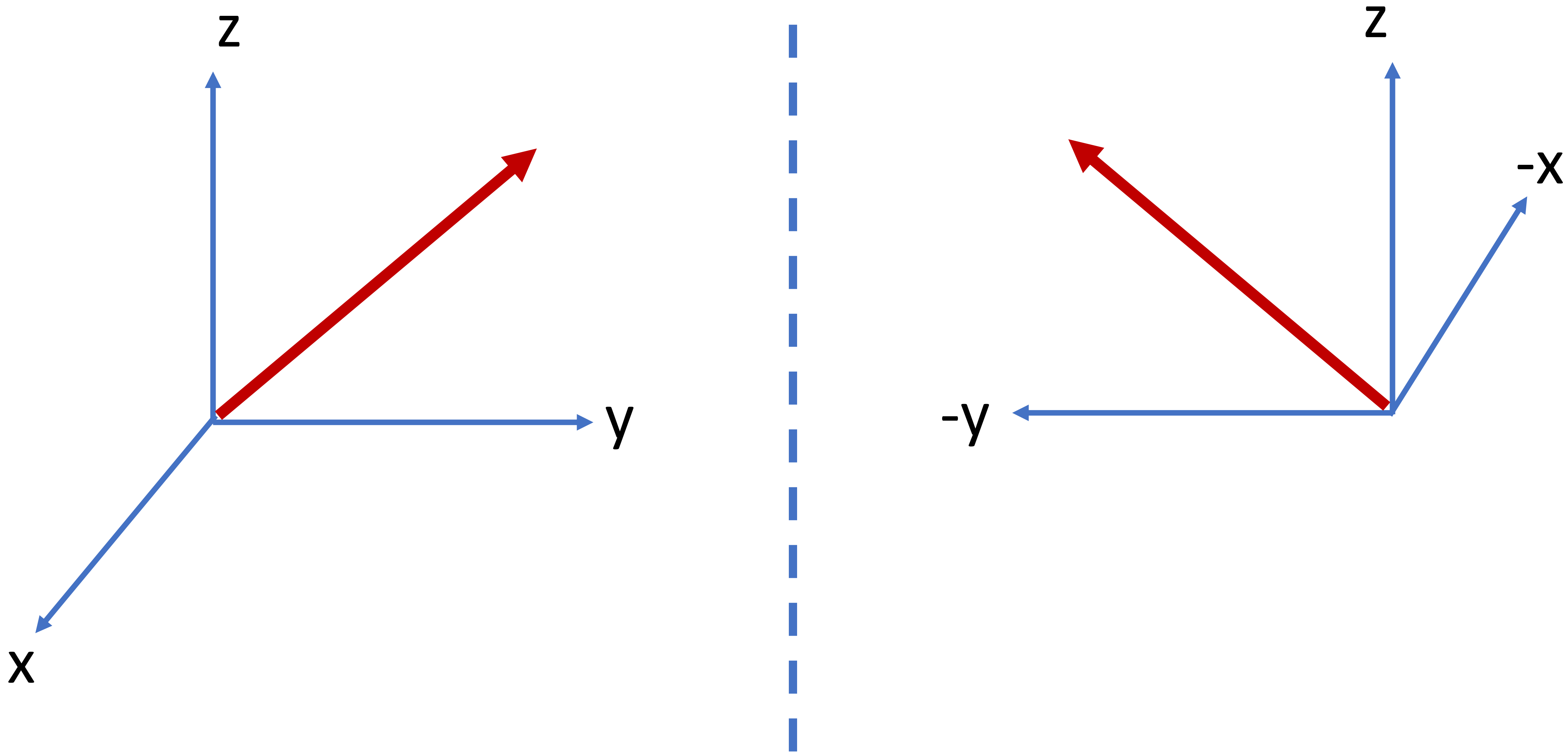
- Parity and its non-conservation in β-decay
- Neutral weak currents and their implication in stable atoms
- Experiments on parity violation in atomic physics

Parity operation = reversal of coordinate axes

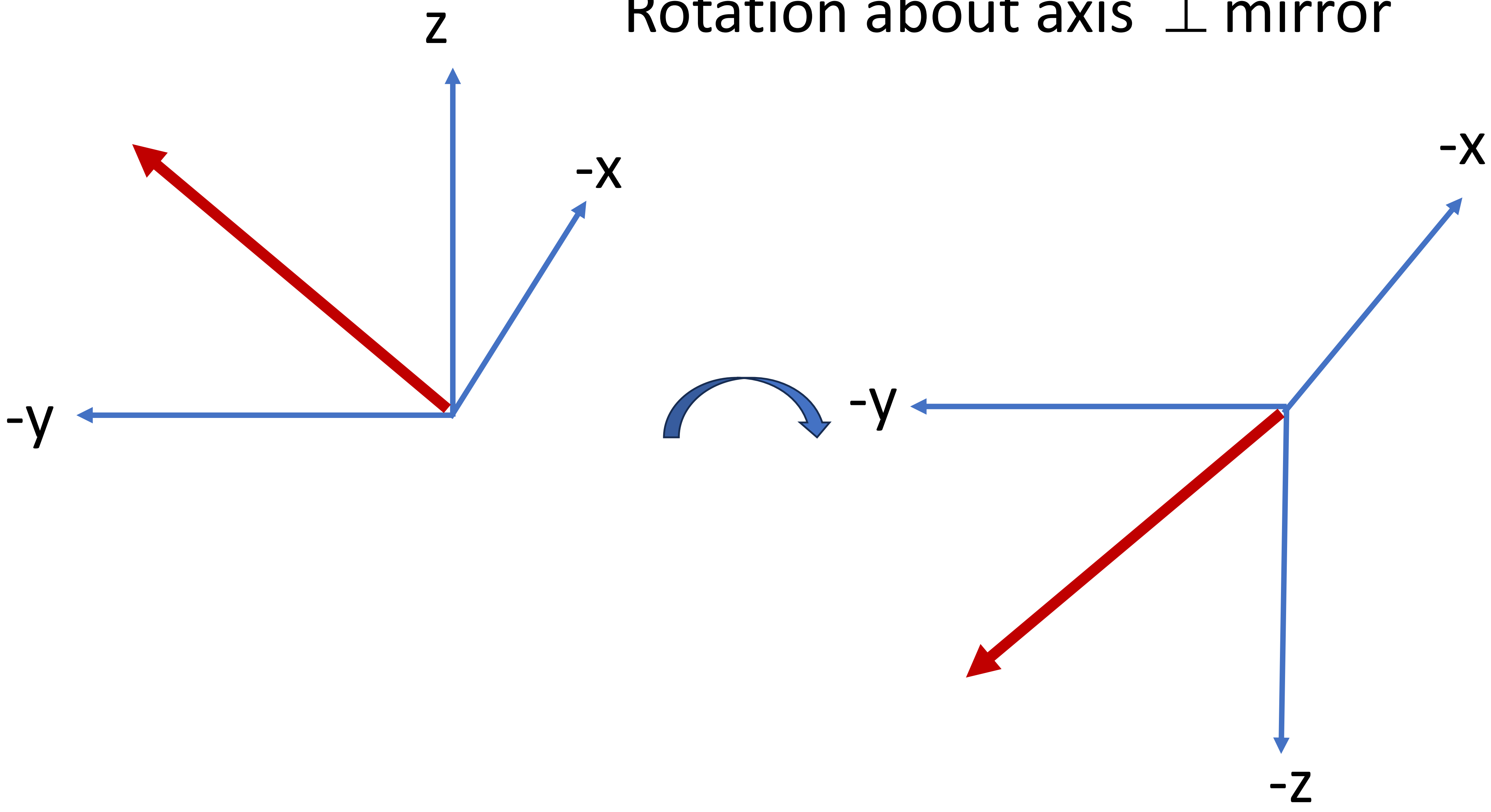
Discrete symmetry operation



Mirror reflection



Rotation about axis $\perp$ mirror



Parity in quantum mechanics

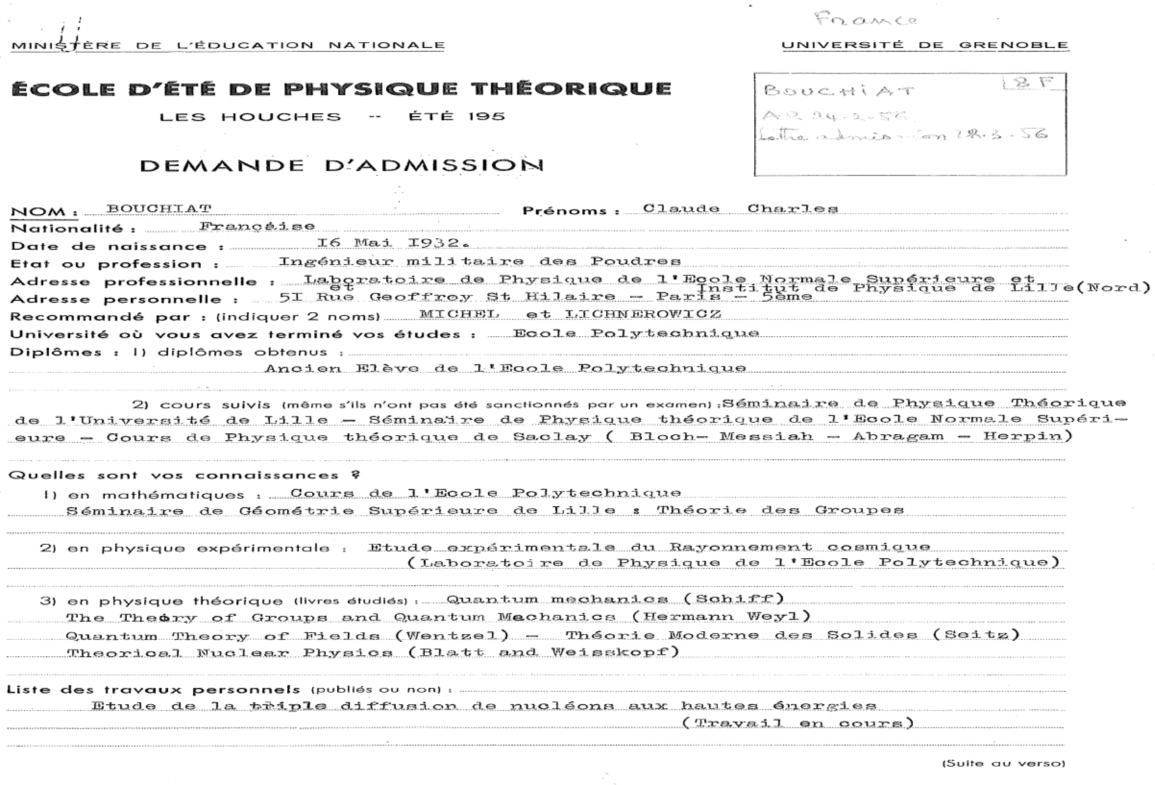
- Wavefunction of a system $\Psi(X, Y, Z)$ (particle or particles) either even or odd under a parity operation
- $\hat{P}\Psi(X, Y, Z) = \Psi(-X,-Y,-Z) = (\pm 1)\, \Psi(X, Y, Z) = P\Psi(X, Y, Z)$
- P = +1 even parity,
- P = -1 odd parity

- Parity is conserved if two experiments in configurations of opposite parity yield the same result.

Parity in quantum mechanics

1956
An auspicious year for parity non conservation

Two young French physicists meet at the *Les Houches* summer school



France

MINISTÈRE DE L'ÉDUCATION NATIONALE

UNIVERSITÉ DE GRENOBLE

BOUCHIAT 18 F
AR 24-2-56
Lettre admission 28-3-56

ÉCOLE D'ÉTÉ DE PHYSIQUE THÉORIQUE

LES HOUCHES -- ÉTÉ 195

DEMANDE D'ADMISSION

NOM : BOUCHIAT Prénoms : Claude Charles
Nationalité : Française
Date de naissance : 16 Mai 1932.
Etat ou profession : Ingénieur militaire des Poudres
Adresse professionnelle : Laboratoire de Physique de l'Ecole Normale Supérieure et Institut de Physique de Lille(Nord)
Adresse personnelle : 51 Rue Geoffroy St Hilaire - Paris - 5ème
Recommandé par : (indiquer 2 noms) MICHEL et LICHNEROWICZ
Université où vous avez terminé vos études : Ecole Polytechnique
Diplômes : 1) diplômes obtenus :
Ancien Elève de l'Ecole Polytechnique

2) cours suivis (même s'ils n'ont pas été sanctionnés par un examen) : Séminaire de Physique Théorique de l'Université de Lille - Séminaire de Physique théorique de l'Ecole Normale Supérieure - Cours de Physique théorique de Saclay (Bloch- Messiah - Abragam - Herpin)

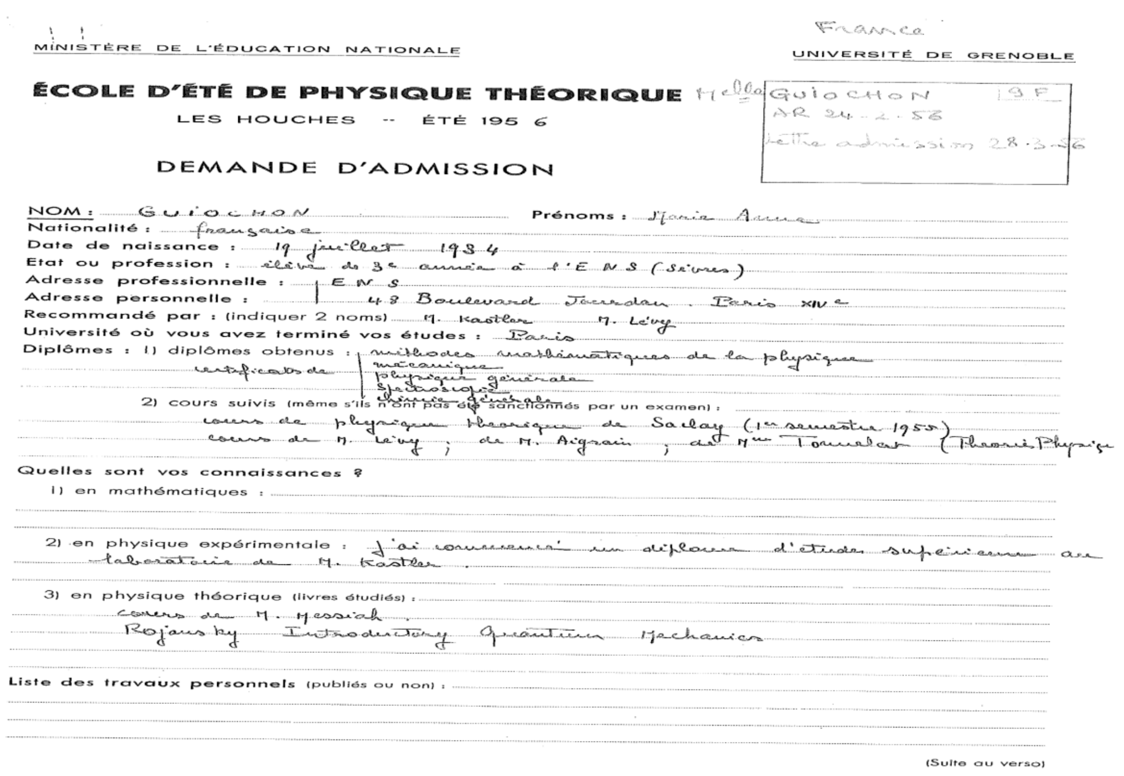
Quelles sont vos connaissances ?
1) en mathématiques : Cours de l'Ecole Polytechnique
Séminaire de Géométrie Supérieure de Lille : Théorie des Groupes

2) en physique expérimentale : Etude expérimentale du Rayonnement cosmique (Laboratoire de Physique de l'Ecole Polytechnique)

3) en physique théorique (livres étudiés) : Quantum mechanics (Schiff)
The Theory of Groups and Quantum Mechanics (Hermann Weyl)
Quantum Theory of Fields (Wentzel) - Théorie Moderne des Solides (Seitz)
Theorical Nuclear Physics (Blatt and Weisskopf)

Liste des travaux personnels (publiés ou non) :
Etude de la triple diffusion de nucléons aux hautes énergies
(Travail en cours)

(Suite au verso)



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GUIOCHON 19 F
AR 24-2-56
Lettre admission 28-3-56

LES HOUCHES -- ÉTÉ 195 6

DEMANDE D'ADMISSION

NOM : GUIOCHON Prénoms : Marie Anne
Nationalité : française
Date de naissance : 19 juillet 1934
Etat ou profession : élève de 3e année à l'E N S (Sèvres)
Adresse professionnelle : E N S
Adresse personnelle : 48 Boulevard Jourdan . Paris XIVe
Recommandé par : (indiquer 2 noms) M. Kastler M. Lévy
Université où vous avez terminé vos études : Paris
Diplômes : 1) diplômes obtenus : méthodes mathématiques de la physique
certificats de mécanique
physique générale
spectroscopie
chimie générale

2) cours suivis (même s'ils n'ont pas été sanctionnés par un examen) :
cours de physique théorique de Saclay (1er semestre 1955)
cours de M. Lévy ; de M. Aigrain ; de Mme Tonnelat (Théorie Physique

Quelles sont vos connaissances ?
1) en mathématiques :

2) en physique expérimentale : j'ai commencé un diplome d'études supérieures au laboratoire de M. Kastler.

3) en physique théorique (livres étudiés) :
cours de M. Messiah .
Rojansky Introductory Quantum Mechanics

Liste des travaux personnels (publiés ou non) :

(Suite au verso)

- T.D. Lee and C.N. “Frank” Yang speculated **parity might not be conserved in weak interactions (θ - τ puzzle)**

- Suggested β-decay of aligned nuclei as one possible test

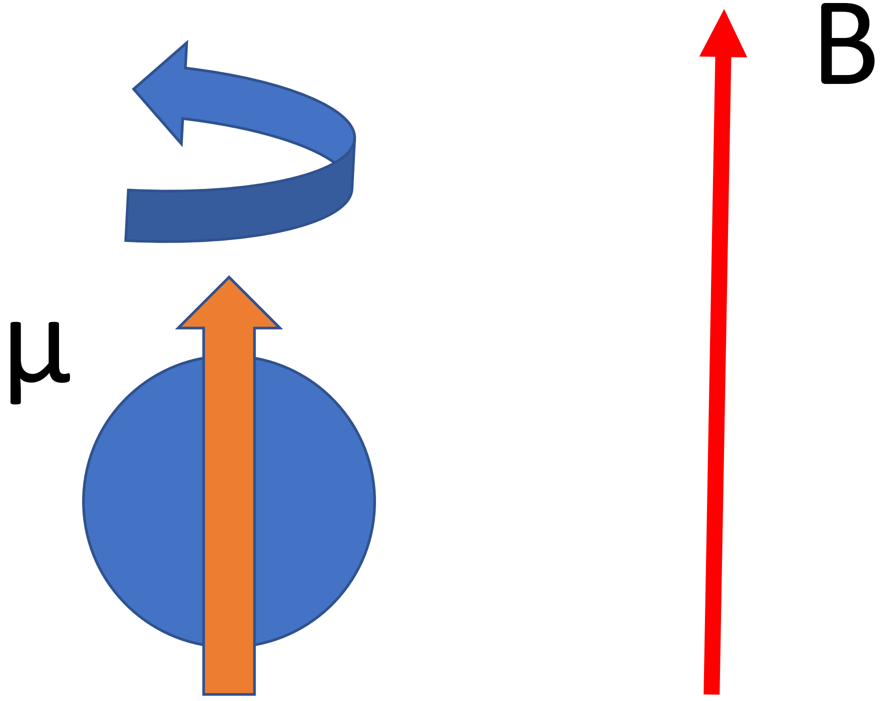
T.D. Lee and C.N. Yang *Phys. Rev.* **104**, 254-258 (1956) and *erratum* **106**, 1371 (1957)

Radioactive decay of ^{60}Co

$$^{60}\text{Co} \rightarrow {}^{60}\text{Ni}^{*} + \beta \rightarrow {}^{60}\text{Ni} + \gamma$$

Nuclear orientation

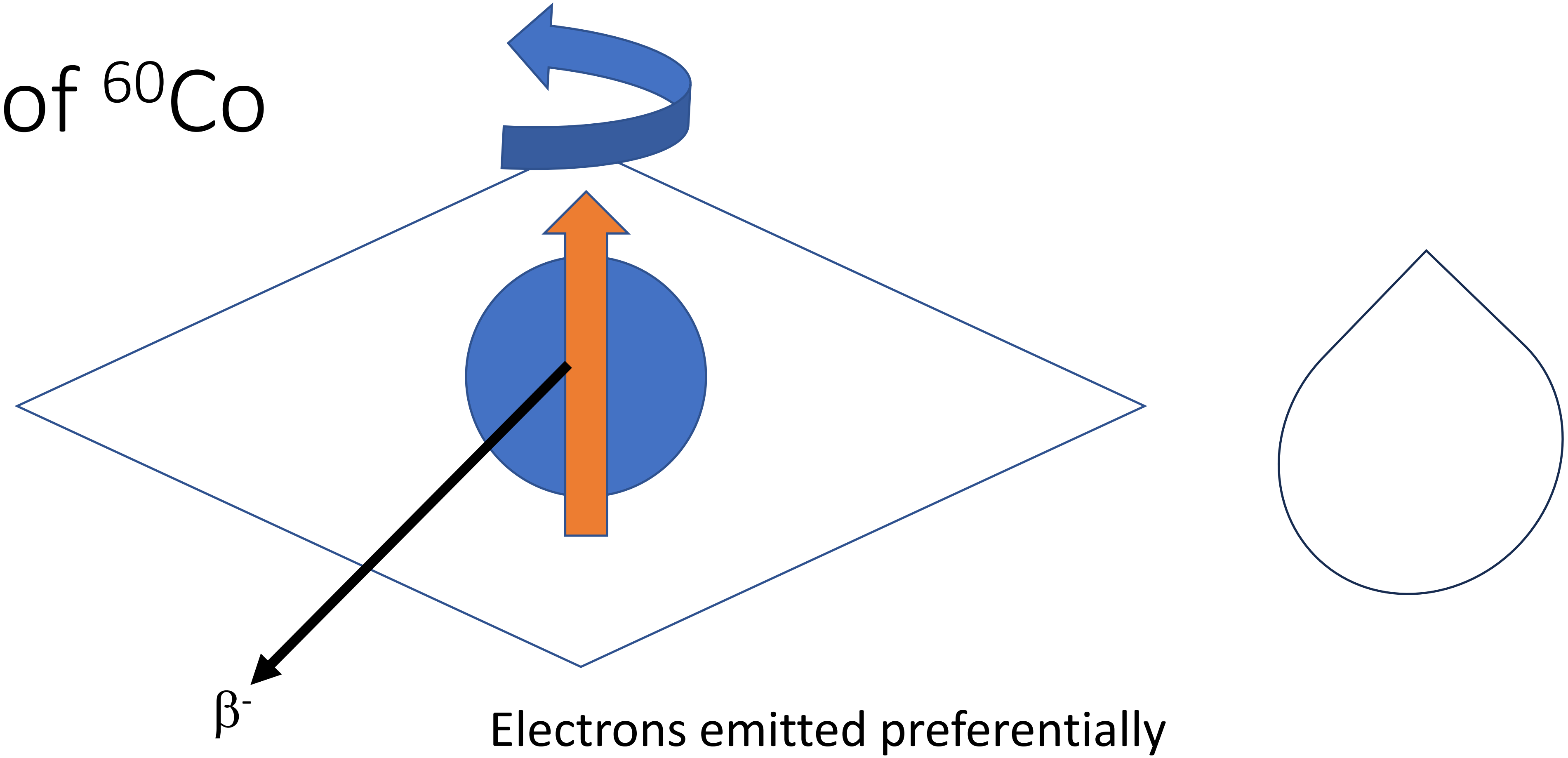
- Cobalt-60 nuclei have a non-zero spin I and magnetic moment μ
- They will tend to align themselves parallel to an external magnetic field, especially at cryogenic temperatures



1957 Historic experiment performed at NBS

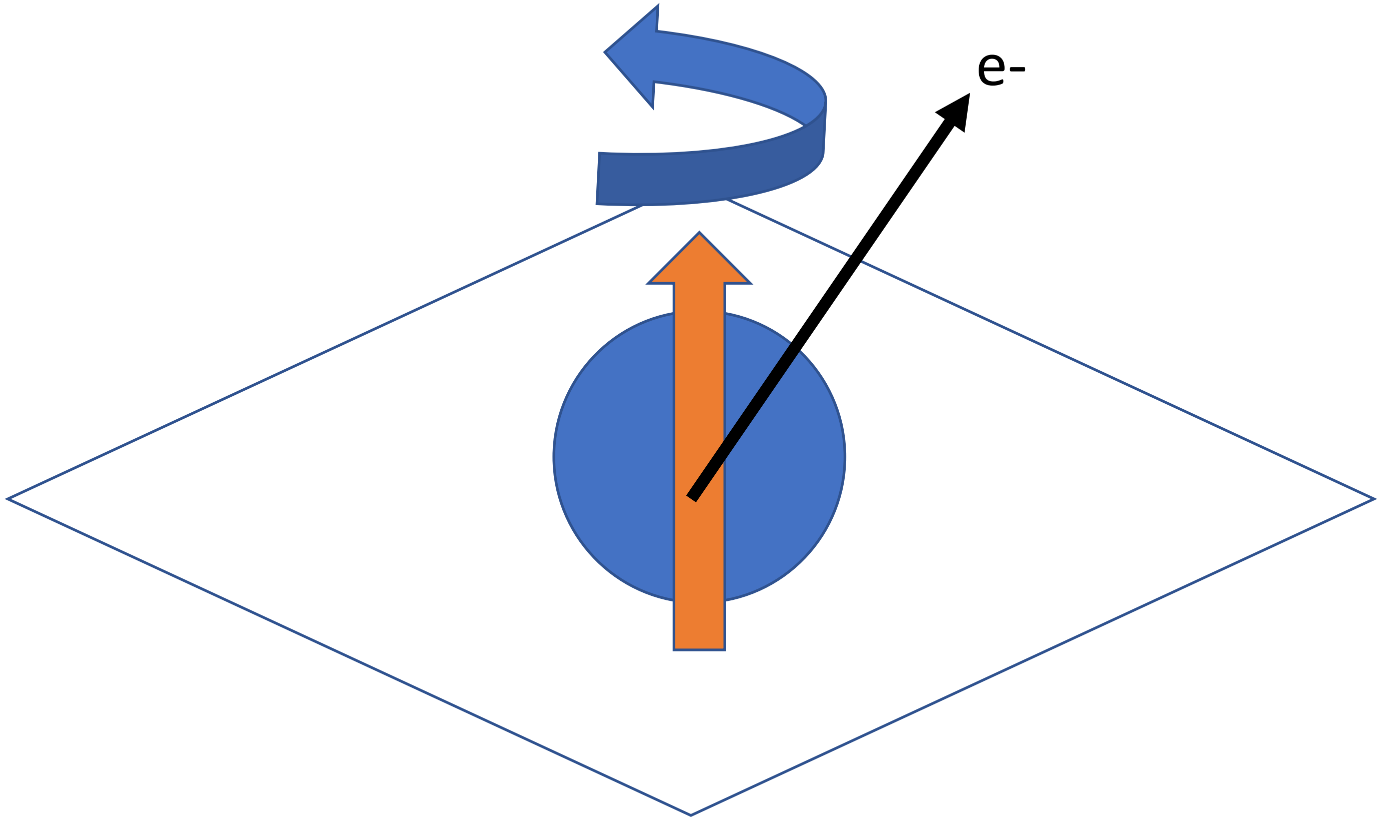
C.S. Wu *et al.* *Phys. Rev.* **105** 1413-1415 (1957)

β-decay of ^{60}Co



Electrons emitted preferentially
in the opposite direction to the nuclear spin

Mirror image β-decay of ^{60}Co never observed



⇓

Parity is not conserved in β-decay

Spin (angular momentum, an axial vector) stays pointing upwards but the direction of the electron (a vector) is reversed.

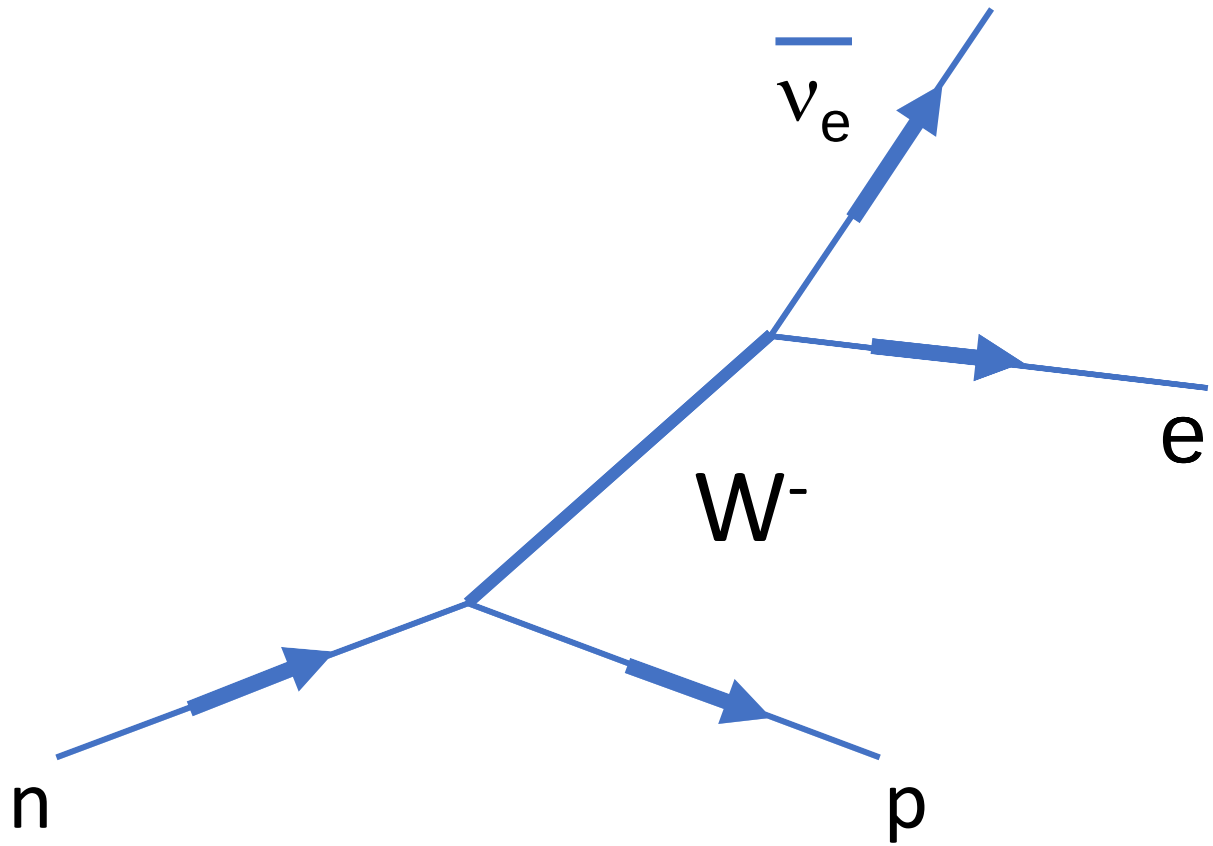
Parity non-conservation↔ weak interaction

- Gravitational, strong, electromagnetic interactions : Parity always conserved

- Weak interaction: Parity sometimes **not** conserved

- **Corrolary :** use the observation of parity violation to isolate the effect of the weak interaction.

β decay is mediated by a charged weak current



Electroweak unification and weak neutral currents (1961-1972)

- *Jamais deux sans trois*

Not only massive charged bosons

W^+ , W^-

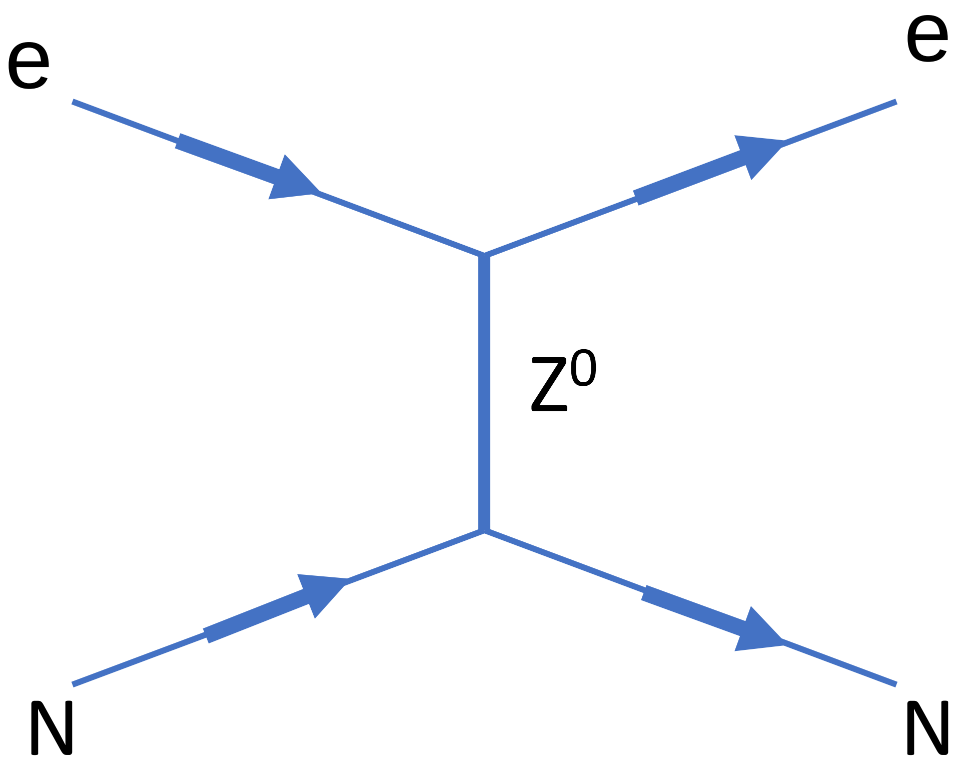
but also a massive neutral boson

Z^0

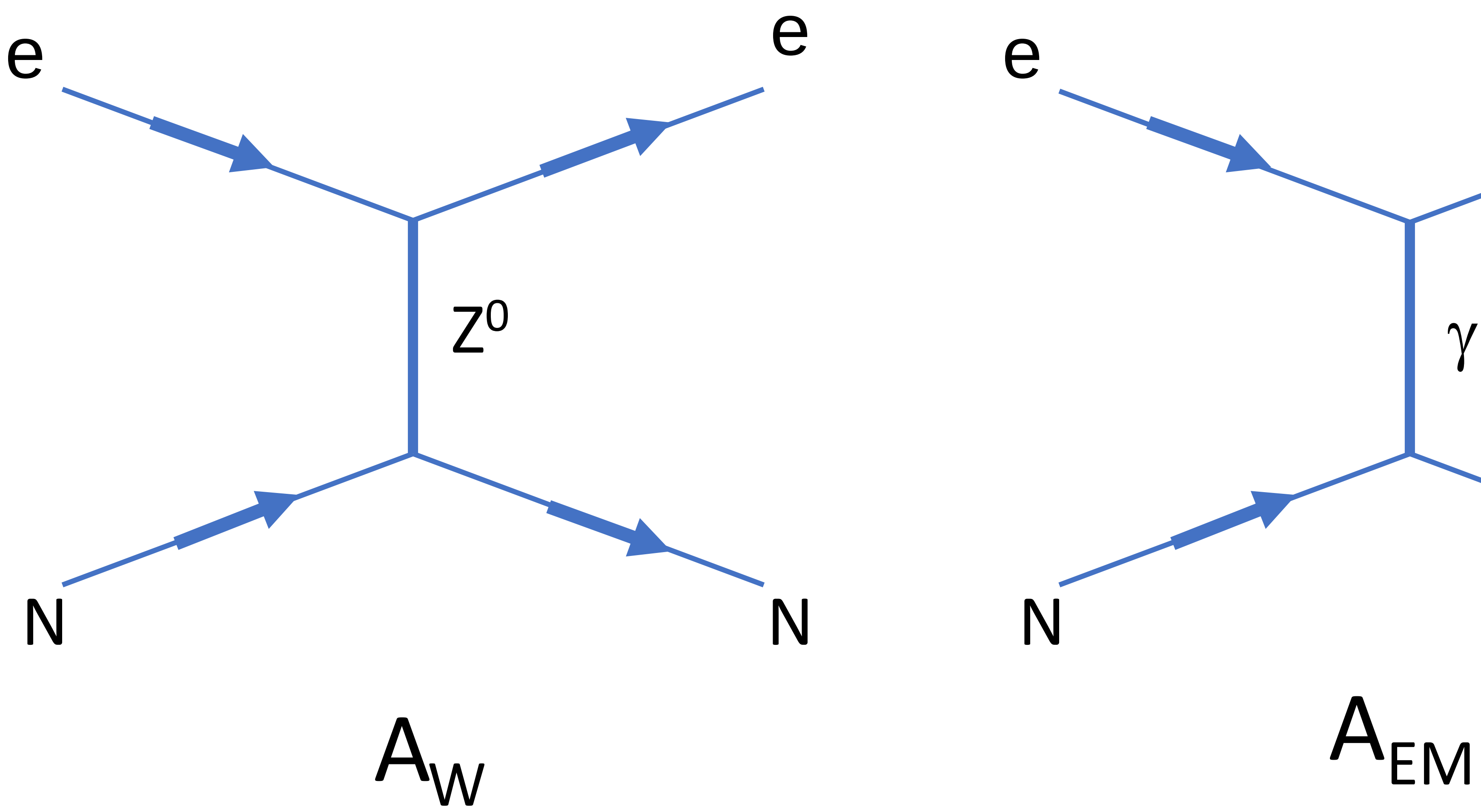
$M_Z \approx 100\ m_p$, hence the name *heavy light*

1972 Marie-Anne and Claude Bouchiat quantify how Z^0 would modify the optical properties of atoms.

Weak neutral current in an atom with a stable nucleus

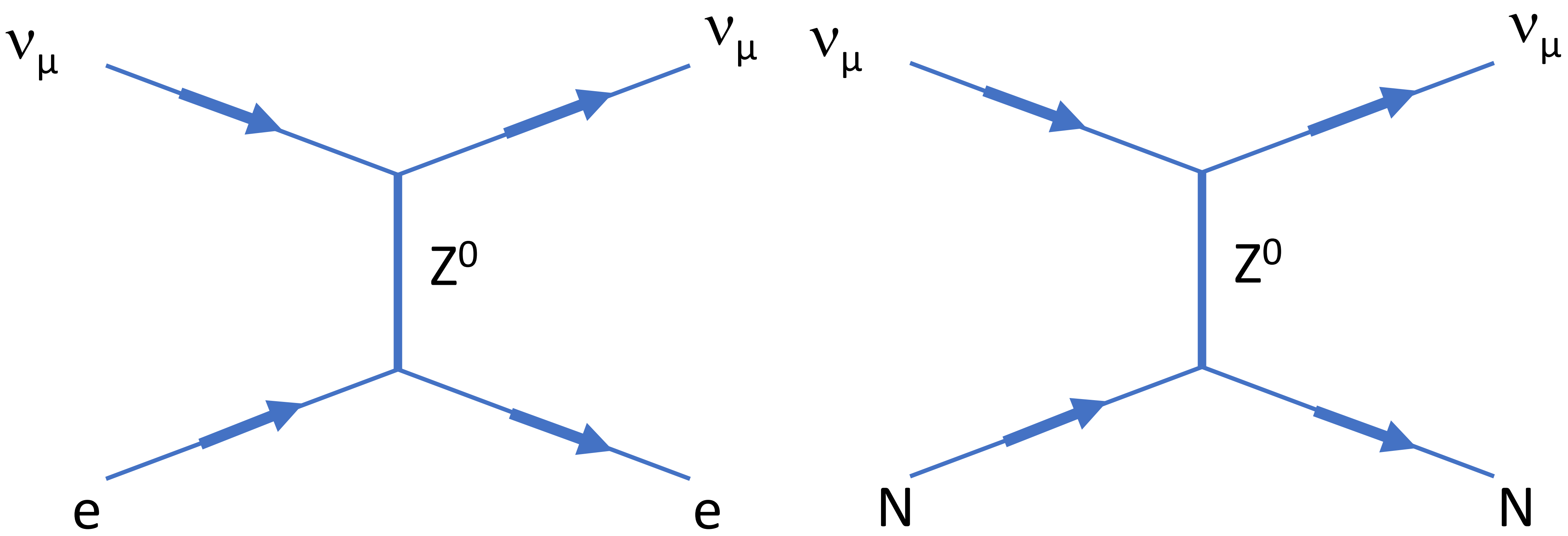


In a stable atom neutral weak currents Z^0 compete with photon exchange between electrons and nucleus



First observation of neutral weak currents Z^0 (Gargamelle bubble chamber, CERN)

- Muon neutrino scattered from electrons and (quarks within) nuclei.



December 1972

1973

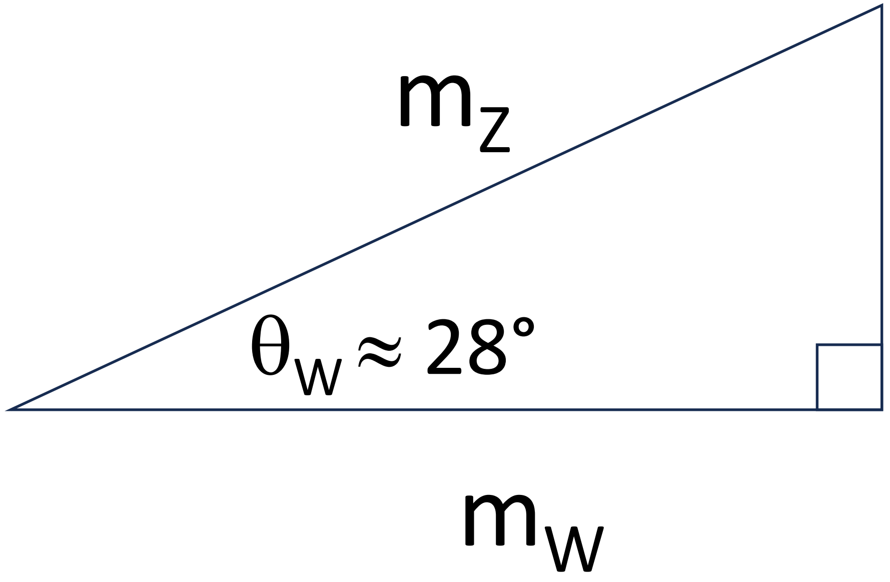
Free parameter of electroweak theory: weak mixing angle θ_W

- $\cos\theta_W = m_W/m_Z$

- $\sin^2\theta_W = 0.23$

$\Downarrow$

$(1 - 4\sin^2\theta_W) = 0.08 \ll 1$



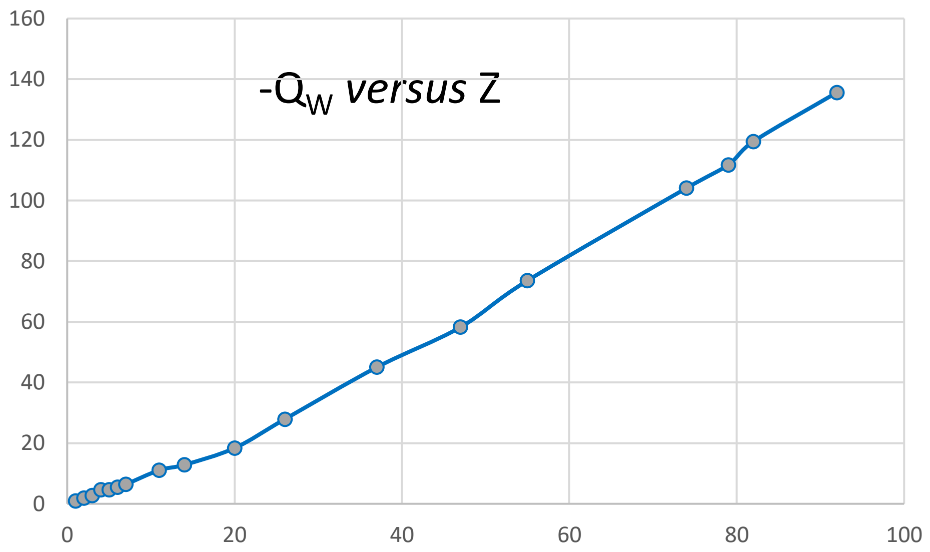
The Bouchiats' Z^3 law

- Weak interaction mixes S- and P-states which are of opposite parity
- Mixing amplitude product of three factors
- Amplitude of the s-electron wavefunction at the origin $\psi_S(0) \propto Z^{1/2}$
- Gradient of the p-electron wavefunction at the origin $d\psi_P(0)/dr \propto Z^{3/2}$

- **Nuclear weak charge** $Q_w = -N + (1-4\sin^2\theta_W)Z \propto -N$

- $E_1^{PV} = C\, K_r Z^2 Q_w \propto Z^3$

  K_r relativistic enhancement factor



- **Study optical transitions in heavy atoms**
- **H, D notable exceptions – theory attractive, experiments so far too hard**

M.A. Bouchiat and C. Bouchiat *Journal de Physique* **35** 899-927 (1974) and **36** 493-500 (1975)

Weak neutral currents modify atomic transitions rates

- Allow very slightly otherwise forbidden transitions

- Transition rate $\propto |A_W|^2 < 10^{-22} |A_{EM}|^2$

- Unobservably small

cf. size of signals in LIGO/Virgo gravity wave detection

How do you isolate the PV effect?

- Bouchiat and Bouchiat suggested using **interference** between EM and electroweak-induced transition amplitudes.

$$|A_{EM} + A_W|^2 = A_{EM}^2 + A_W^2 + \mathbf{2\,Re(A_{EM}A_W{}^*)}$$

- Measure ratio **$2Re(A_{EM}A_W{}^*)$ /** $A_{EM}^2 = 2ReA_W{}^*/A_{EM}$

- Electric dipole (E1) transition $|A_W/A_{EM}| \approx 10^{-11}$

How can you increase the PV asymmetry?

- By studying transitions where A_{EM} is small

- Allowed magnetic dipole (M1) transitions Tl (Z=81), Pb (Z=82), Bi (Z=83) :

$$|\mathrm{Re}\, A_W/A_{EM}| \approx 10^{-7}$$

- Or even smaller still

- Forbidden magnetic dipole transitions Cs (Z=55), Tl :

$$|(\mathrm{Re}\, A_W)/A_{EM}| > 10^{-4}$$

but much lower signal $\propto |A_{EM}|^2$

How do you extract Q_w from measurements?

- Atomic structure calculations of E_1^{PV}/Q_w and vector polarisability β.

- Easiest for alkali atoms e.g. Cs (6s) but still extremely hard.

 (now at the sub-1% level)

- More challenging for Tl ([$6s^2$] 6p),
- Even tougher for Pb ([$6s^2$] $6p^2$) and tougher still for Bi([$6s^2$] $6p^3$)

- *Ab initio* or semi-empirical C. Bouchiat and C.A. Piketty

PV experiments worldwide

- Paris PV experiment started in 1973

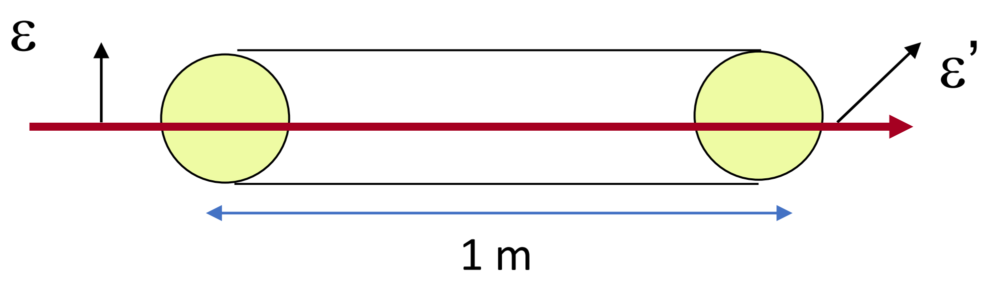
- Following B&B 1974-75 papers other optical PV experiments began in

  Zurich, Novosibirsk, Oxford, Berkeley, Seattle, Moscow

Two types

- Optical rotation
- Stark interference

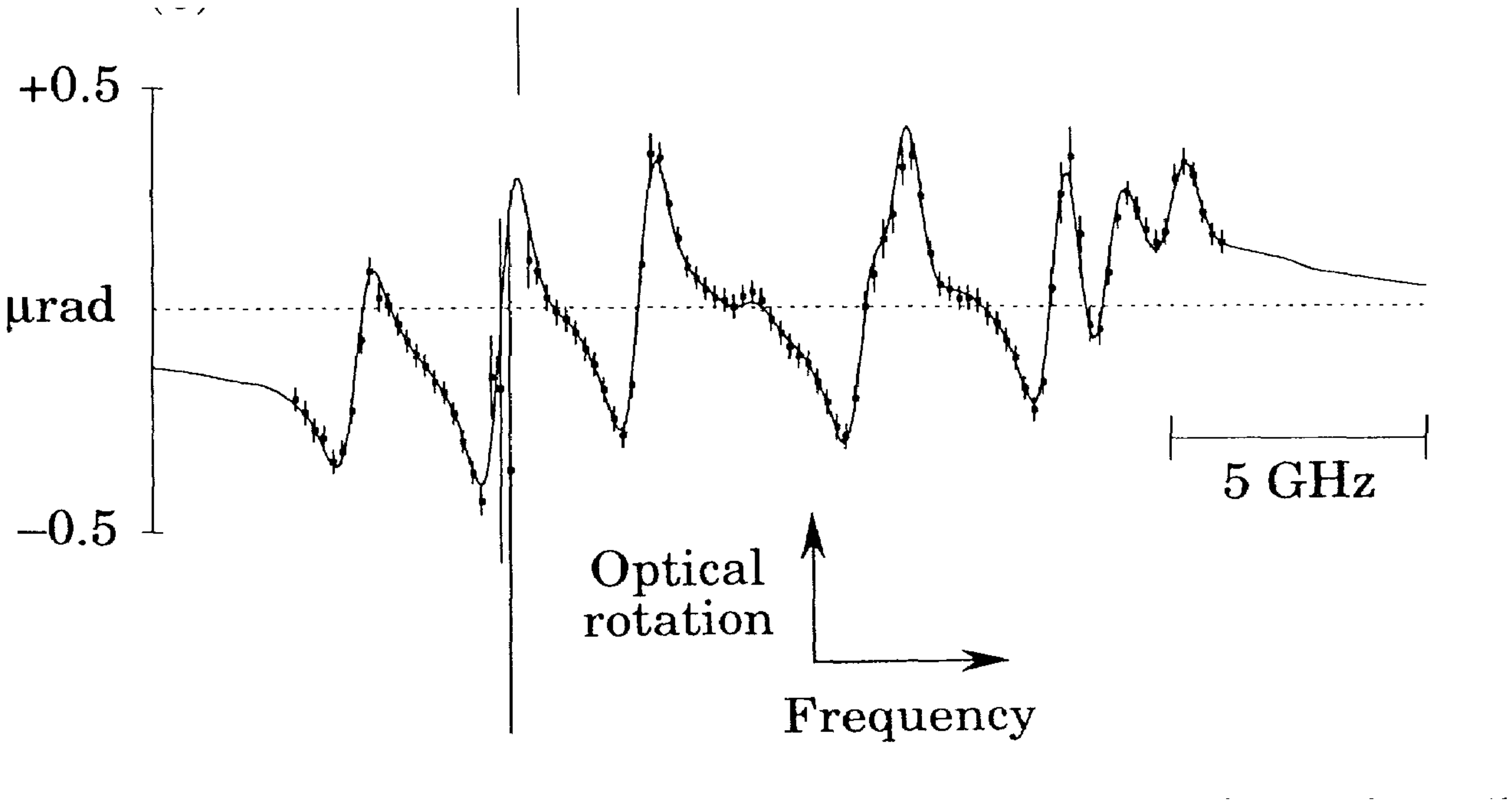
Optical rotation experiments: the simplest approach



Oven with vapour and buffer gas placed between crossed polariser and analyser

- Allowed M1 transition (Tl, Pb, Bi, Sm): circular birefringence – **optical activity** of an atomic vapour 10^{-7} rad/ absorption length (Oxford, Moscow, Novosibirsk, Seattle)
- D.N. Stacey « *It is better to measure* 10^{-7} *of something than* 10^{-4} *of nothing* »
- Are your sure to recognize that something?
- Challenge of systematic effects, conflicting results of early experiments late 1970s
- To isolate PV effect,
  - (i) compare rotation with/without atomic vapour.
  - (ii) scan laser frequency and exploit lineshape,

Optical rotation on the 876 nm line in bismuth



M.J.D. MacPherson *et al. Phys. Rev. Lett.* **67**, 2784-2787 (1991)

Oxford group

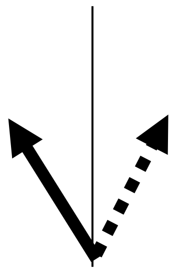
- Uncertainty 1-3% by the 1990s in Tl, Pb and Bi

Stark interference experiment : harder but ultimately more reliable

- Forbidden magnetic dipole transition (Cs 6s-7s, Tl 6p-7p)

  Asymmetry ~5×10^{-4} but no signal! (1 absorption length = 1 million km)
- Clever trick : apply an electric field to make the transition slightly allowed
- Look for the interference $A_W A_{Stark}$.
- A_W/A_{Stark} ~ 10^{-5} to 10^{-6} but…
- The effect changes sign under the reversal

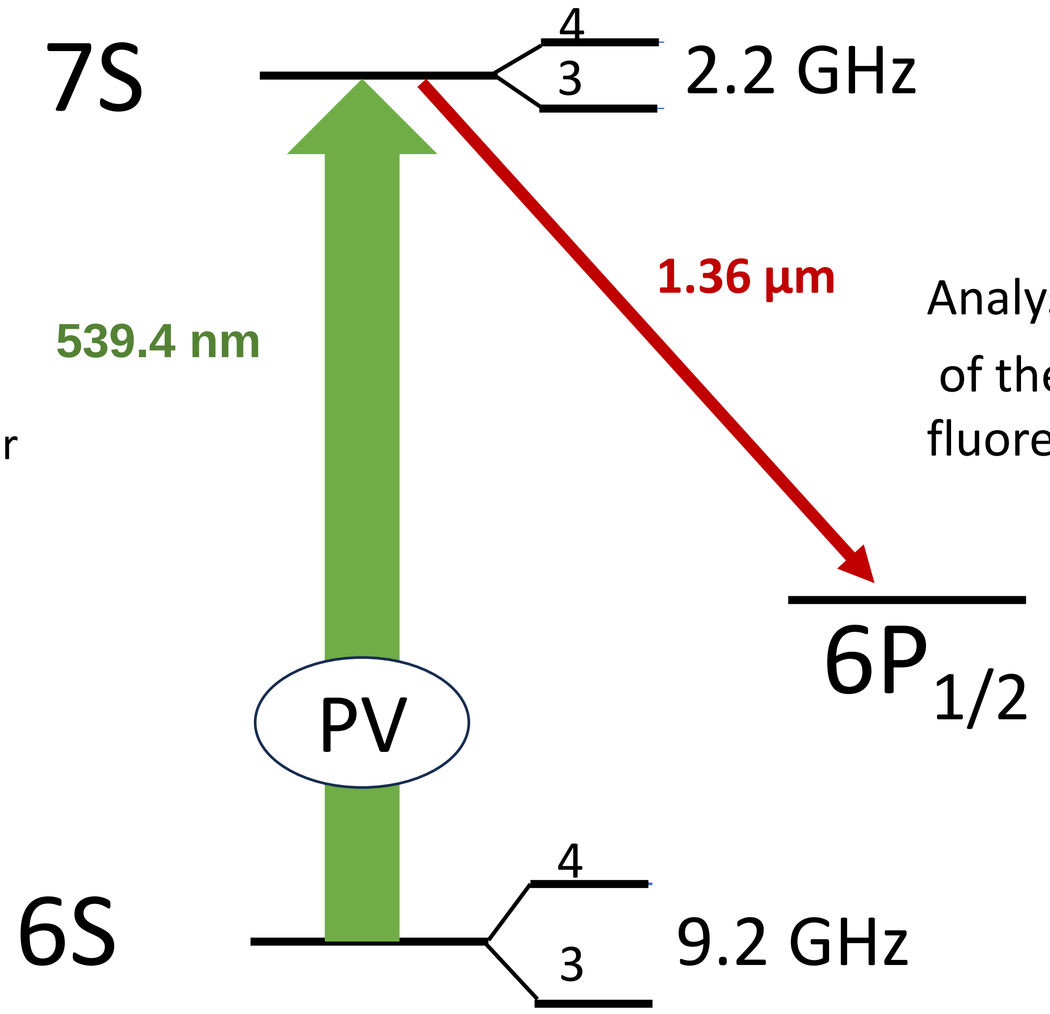
$$E \rightarrow -E.$$



Very powerful discriminant against systematic effects.

First Cs parity violation experiment (Paris 1973-1983)

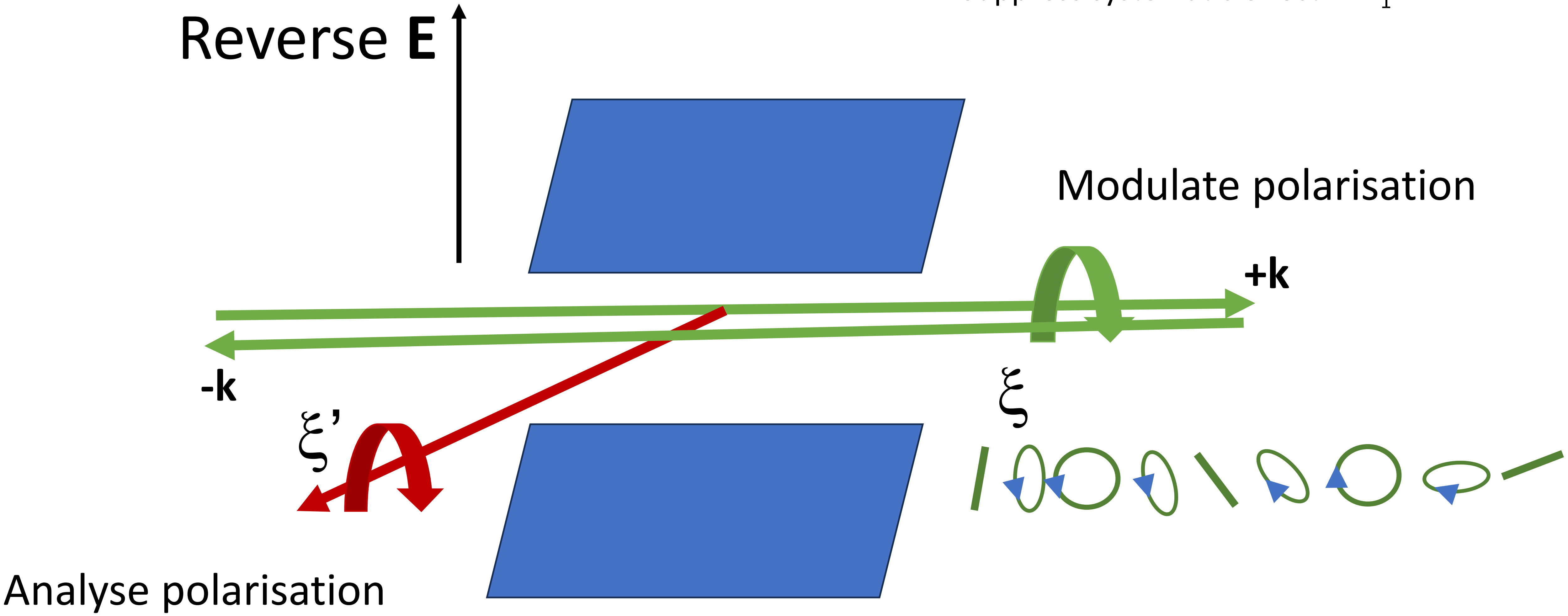
Excite with laser of circular polarisation ξ

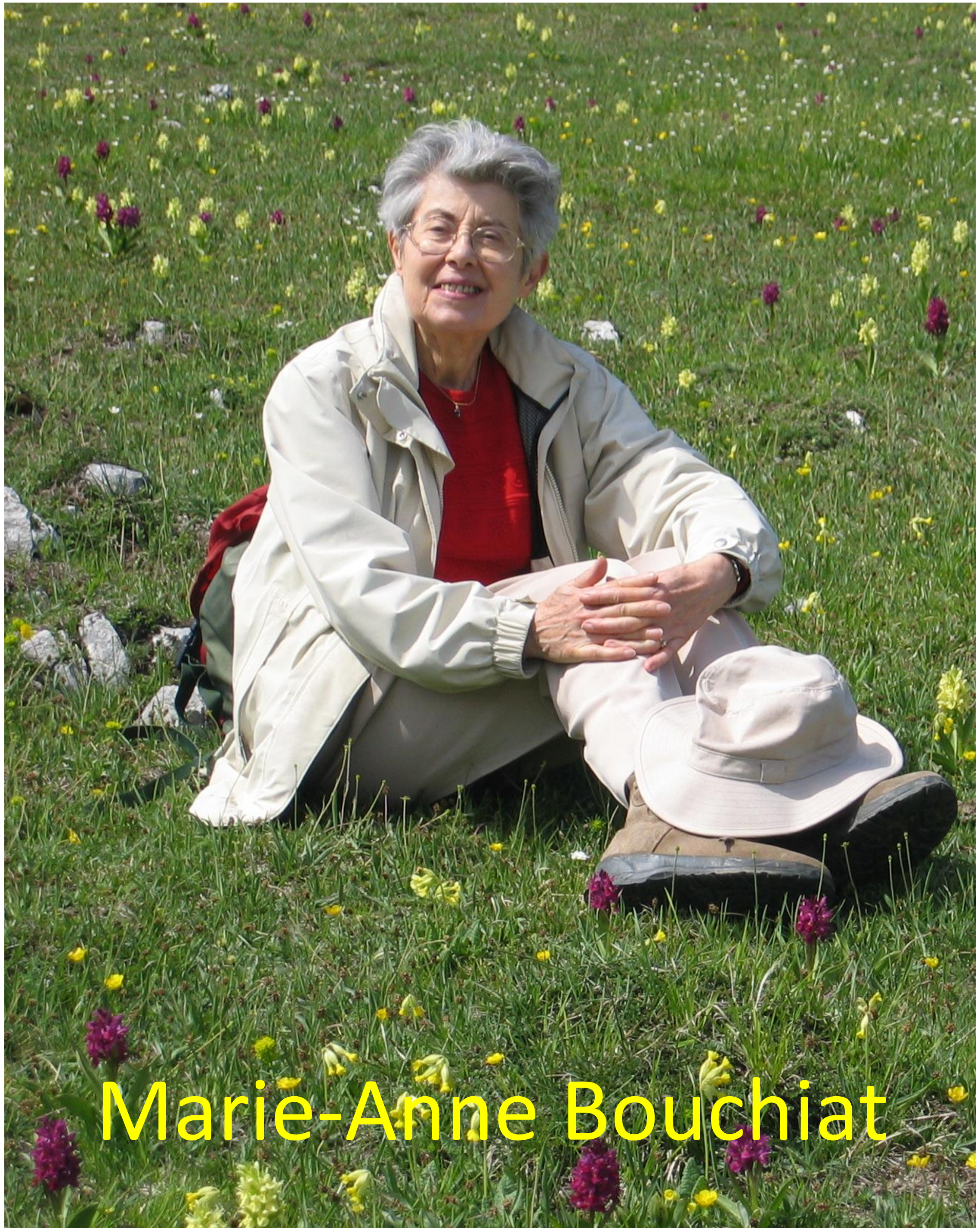


Analyse circular polarisation ξ' of the fluoresence

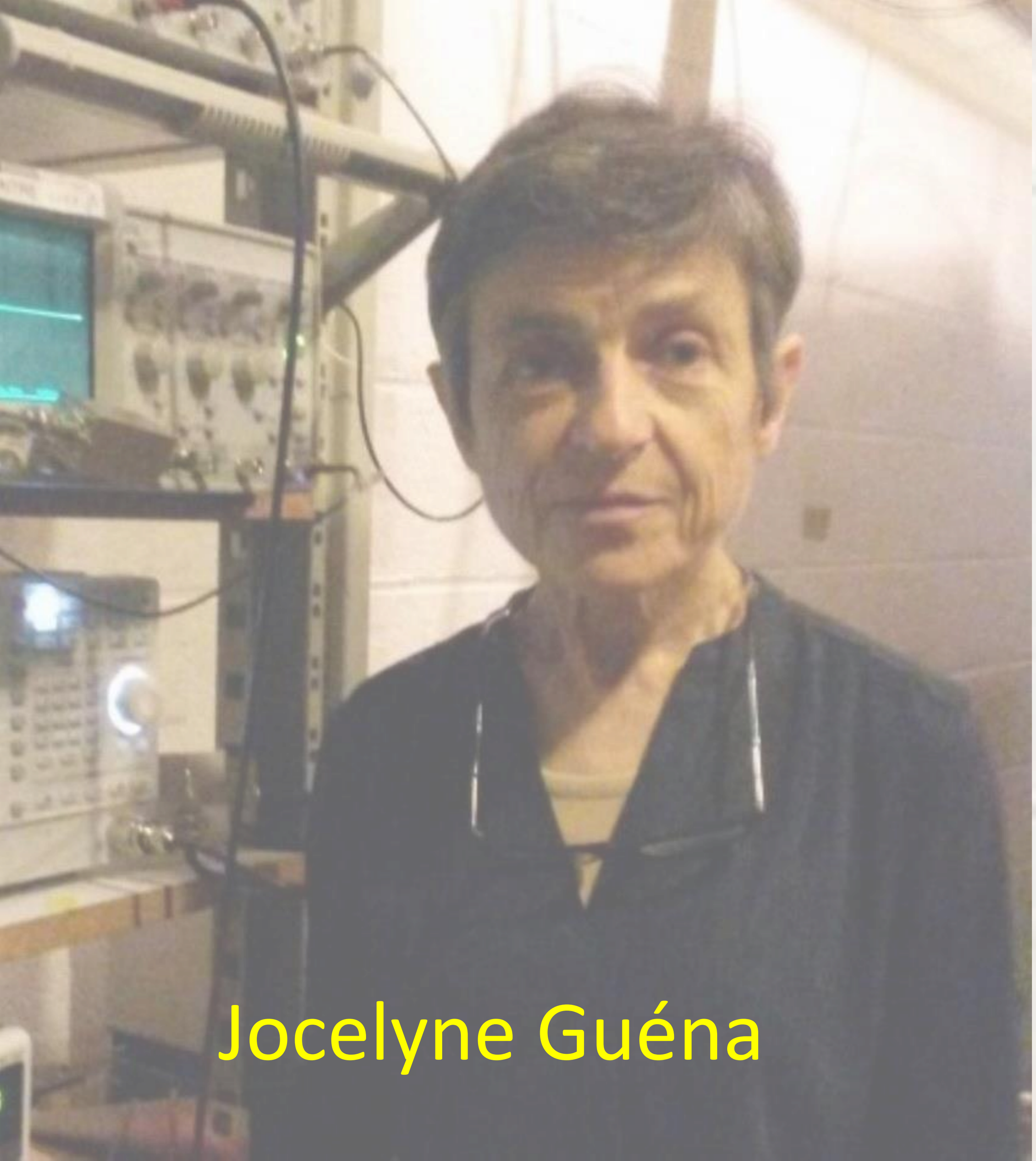
Experimental geometry

- Circular dichroism and Stark interference
- Multi-pass cell (100 fold)
- Increase PV signal
- Suppress systematic effect $\propto M_1\mathbf{k}$




Marie-Anne Bouchiat


Lionel Pottier



Jocelyne Guéna

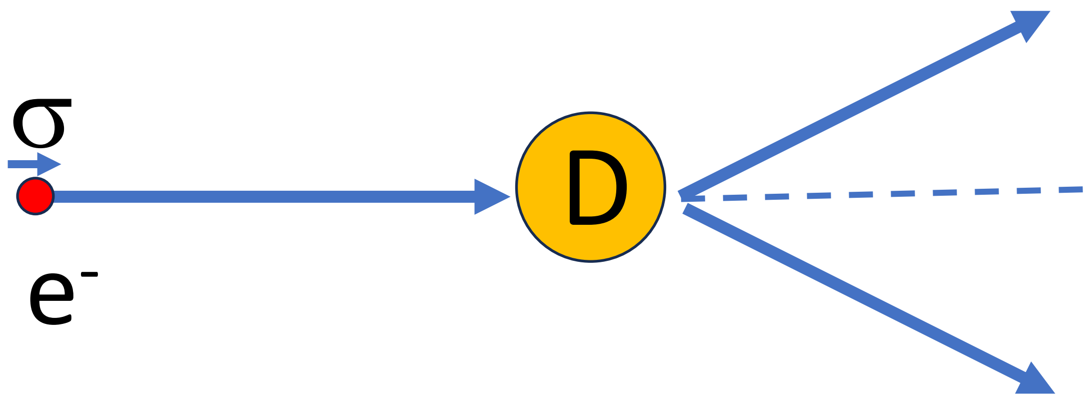
Larry Hunter

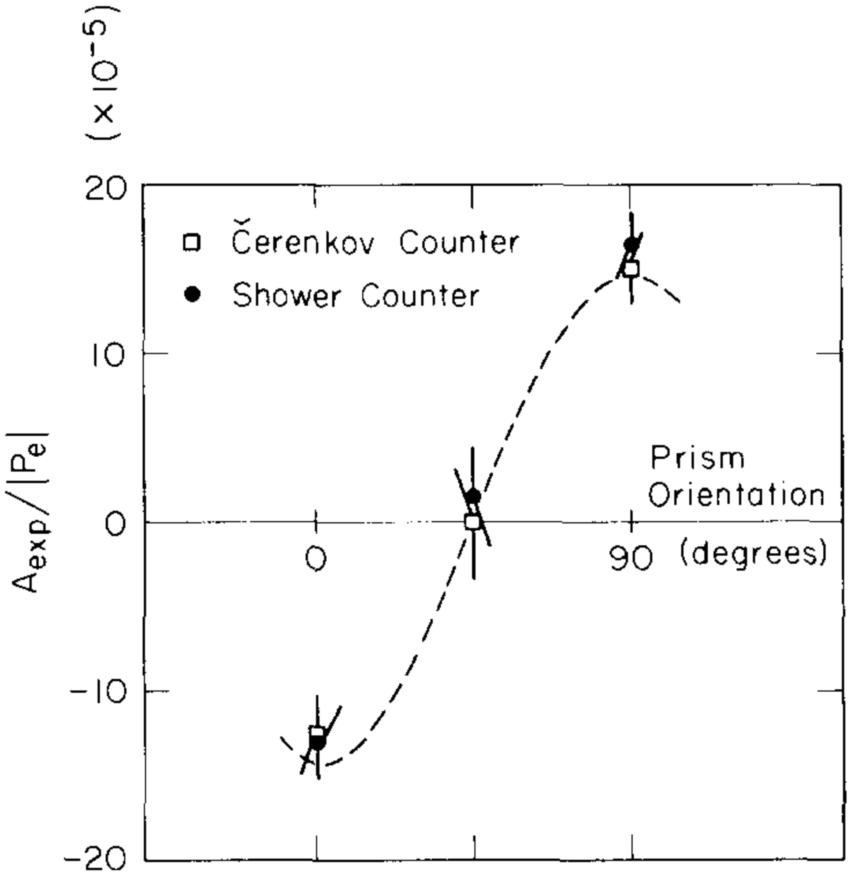
- By the early 1980s, after having reduced all imaginable systematic effects to an acceptable level, the Paris group was at last ready to measure PV.
- In the sub-basement of the ENS physics department, Marie-Anne Bouchiat, Lionel Pottier, Jocelyne Guéna and Larry Hunter took data 24/7 for 6 weeks, once in 1982 and again in 1983.
- Two different hyperfine components of the transition (4-4 and 4-3) studied as systematic effects very different
- Uncertainty ≈20% per transition
- 12% **for the weighted average**.

$$\mathrm{Im}\, E_{pv}^{1}/\beta = -\,1.52 \pm 0.18\ \mathrm{mV/cm}.$$

M.A. Bouchiat *et al. J. Physique* **46**, 1897-1924 (1985), **47**, 1175-1202 and 1709-1730 (1986)

Scattering of high-energy (19.4 GeV), longitudinally polarised electrons scattering from deuterium (Stanford Linear Accelerator)

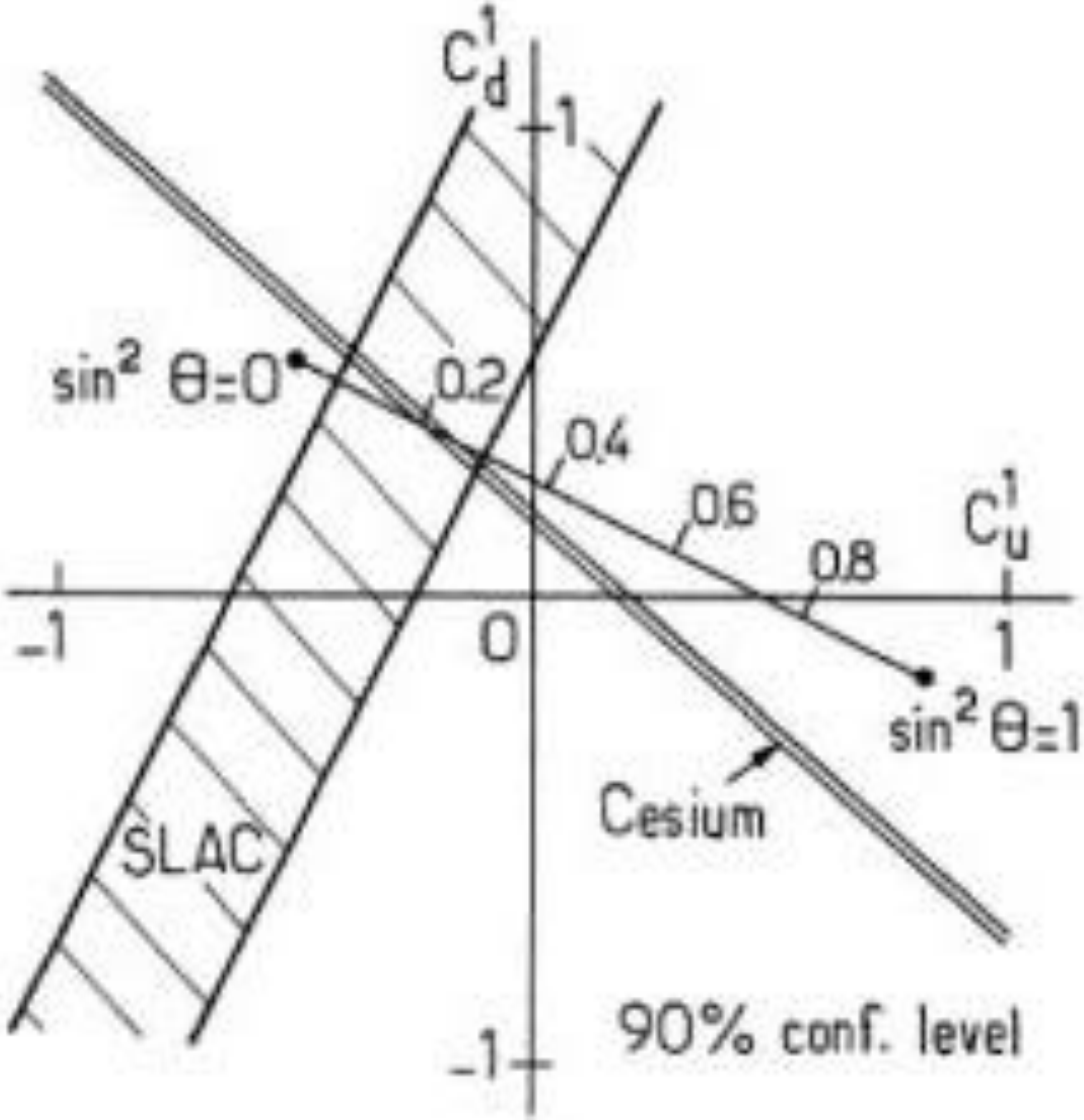




- 10^{-4} left-right scattering asymmetry when electron helicity σ reversed
- First evidence of neutral weak currents in electron-nucleus system

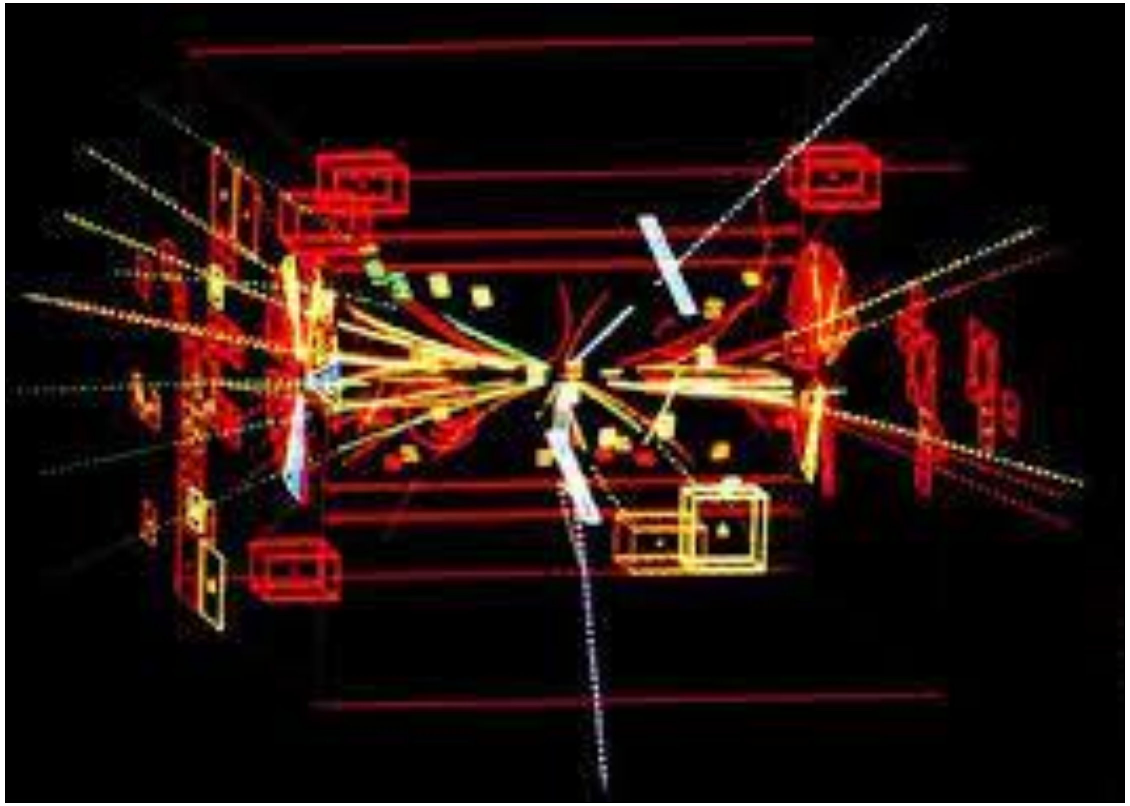
C.Y. Prescott *et al. Physics Letters* **77B**, 347-352 (1978)

Complementarity of low- and high-energy experiments



4th May 1983 Discovery of first Z boson at CERN

- Proton-anti-proton collider
- Observe decay products of short-lived massive bosons.
- See Peter M. Watkins, « Story of the W and Z »(Cambridge 1986).



Why pursue PV experiments?

- At uncertainties below 10%, test radiative corrections to the Weinberg-Salam model in the low-energy limit.

- Set limits on the mass of extra neutral Z bosons.

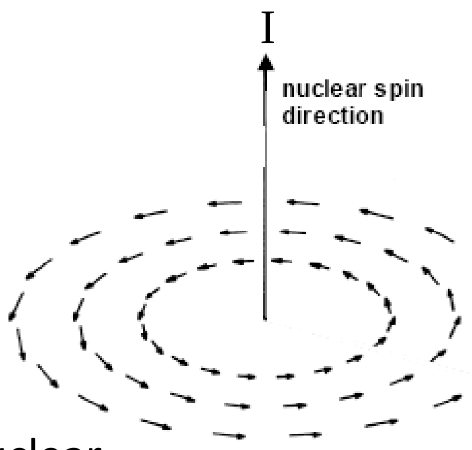
- At the few percent level of uncertainty, look for nuclear spin-dependent effects (nuclear anapole moment)

Nuclear anapole moment

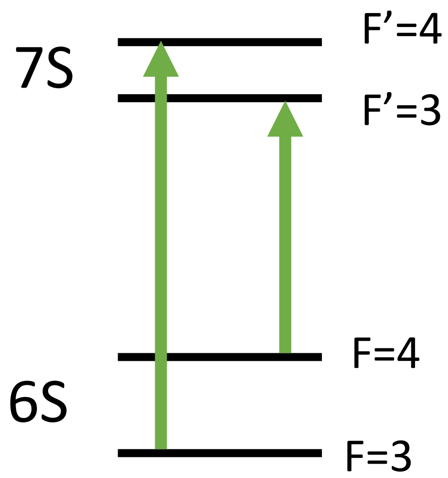
Ia B. Zel'dovich *J. Exptl. Theoret. Phys.* (U.S.S.R.) **33**, 1531-1533 (December, 1957)

- Effect of the weak interaction within the nucleus – chiral magnetism
- EM interaction = photon exchange between the electron and the nucleus modifies the EM absorption properties of the atom
- Effect $\propto Z^2 = (Z^{1/2} \times Z^{3/2})$ depends on nuclear spin
- About 2% of that due to Q_w in experiments on Cs :
- Difference between PV asymmetries for different hyperfine components of an optical transition
- Suggestion to observe it by NMR of a Cs atom trapped in a single crystal of helium – uniaxial hexagonally close packed phase.

  M.A. Bouchiat and C. Bouchiat *Eur. Phys. J. D* **15**, 5-18 (2001)



Parity violating nuclear spin magnetization



Michigan/Boulder cæsium PV experiments (1980-1997)

Carl Wieman and colleagues

- Circular dichroism experiment using crossed **E** and **B** fields

(Principle M.A. Bouchiat, M. Poirier and C. Bouchiat *J. Physique* **40**, 1127-1138 (1979)

used in Berkeley expts on thallium 6P-7P)

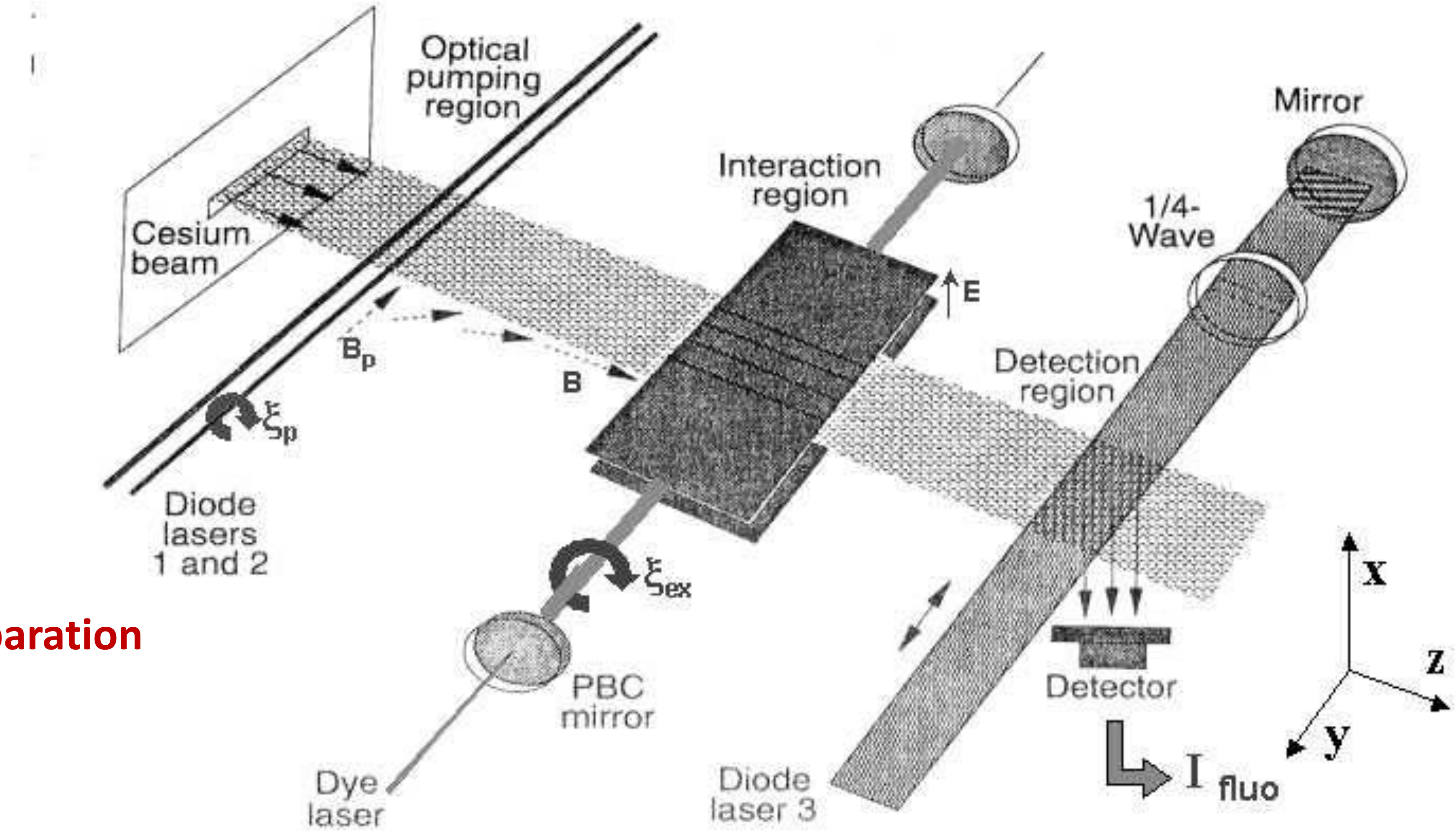
- 3 reversals (circular polarisation, E and B)

- **Atomic beam** clean environment, easy to modify, lower B field (6.4 G) cf. cell (1 kG)
- **High S/N** thanks to huge intra-cavity laser power (2.5 kW), detection efficiency
- PV signal is a tiny difference of large signals (6S -6P fluorescence **at 852 nm**) – bright field detection

1986 8%, 1988 2.5 %

- Later version used optically-pumped beam to populate different magnetic sub-levels $\rightarrow$ **2 more reversals**

Interaction: 2.5 kW green light



Preparation

Detection

Taken from C.S. Wood et al. *Science* **275**, 1759-1763 (1997)
Detailed description in C.S. Wood *et al.* Can. J. Phys. **77**, 7-75 (1999)

Results of Boulder Cs PNC experiments

1986	8 %
1988	2,5 %

1997 experiment with optically pumped beam

High intra-cavity laser power leads to 6S-7S lineshape distortion:

Systematic shift on F=4 - F'=3 (2% per data block) averaged down to a negligible level

For F=3 - F'=4 and F=4 - F'=3	0.5 % per component
Weighted average	0.35%

Current difference w.r.t. Q_w Standard Model -0.3 σ to + 1.2 σ (Toh *et al.* PRL **123** 073002 (2019))

Nuclear anapole moment

Ratio of PV HF amplitudes -1 : $(4.9\pm0.7)\times10^{-2}$ *versus* $(1.6\pm0.3)\times10^{-3}$ theory

Marie-Anne Bouchiat *Il Nuovo Cimento* **35C**, N. 4, 78-84 (2012)

Second Paris Cs PV experiment (1984-2004)

And now for something completely different - but step by step.

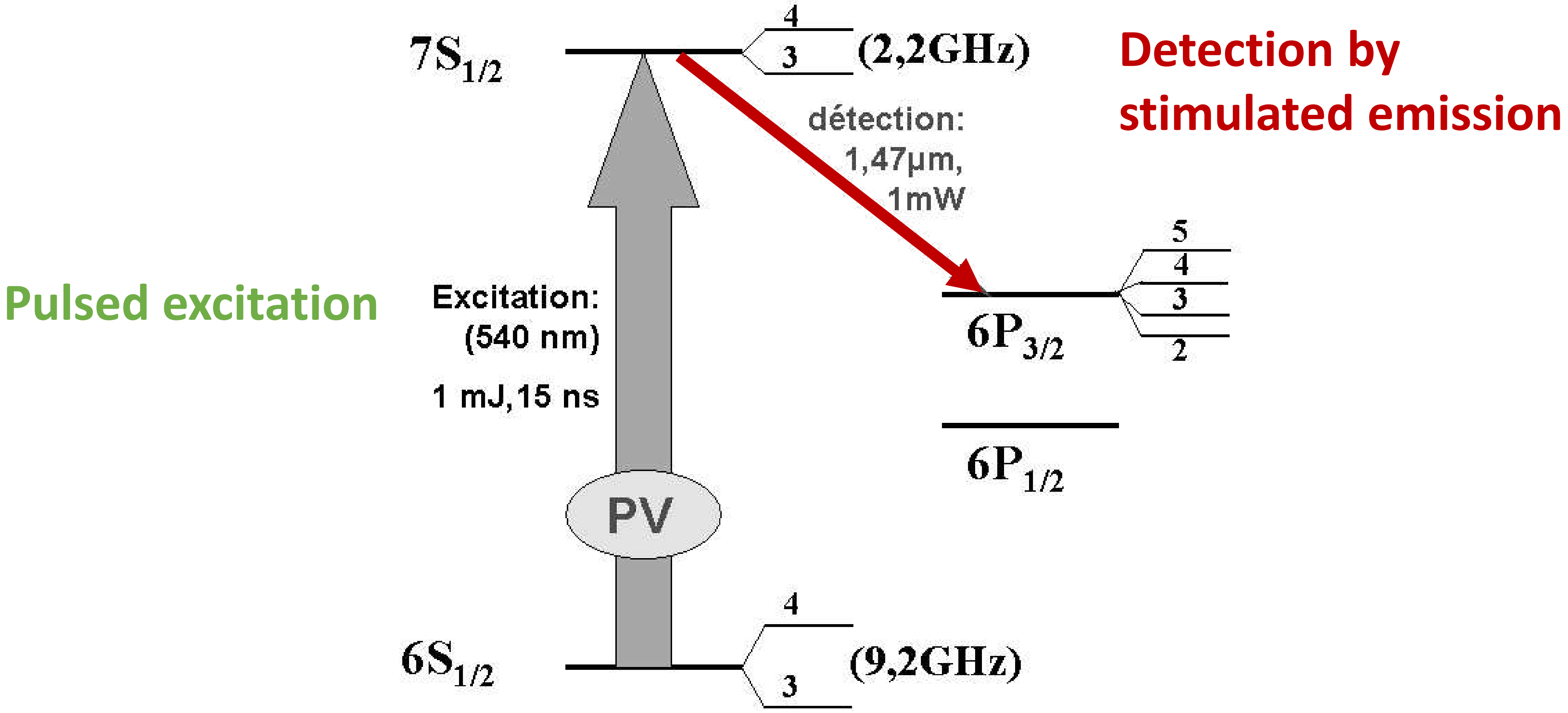
Thèse de doctorat d'Etat ENS 1991

PhD students
- Michel Lintz (later permanent member)
- Dominique Chauvat (RIP)
- Erwan Jahier
- Stefano Sanguinetti

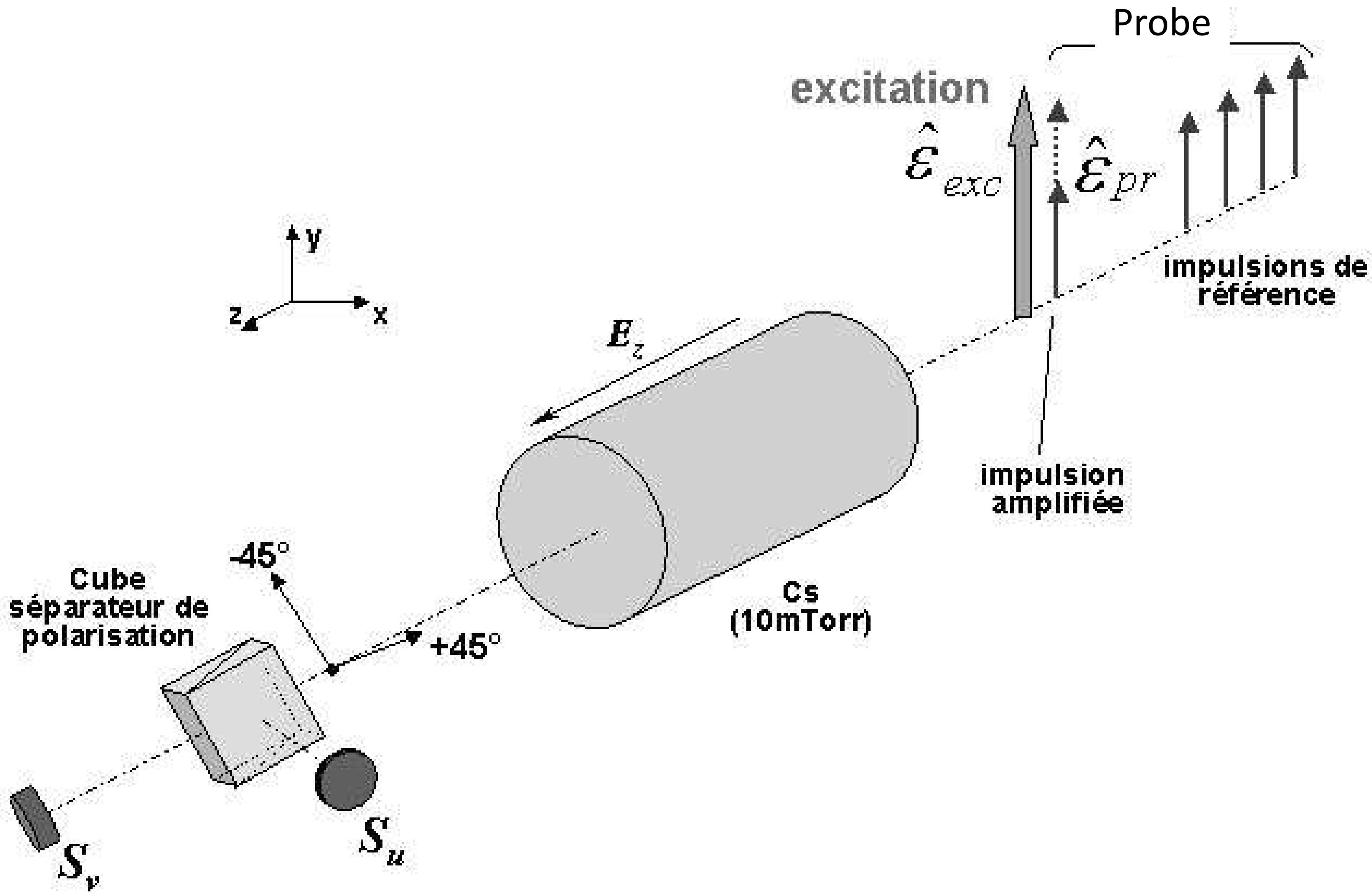
Postdocs and visitors
- Emlyn Hughes
- Sven Redsun
- M.P.
- Sergei Kanorsky
- Aram Papoyan
- David Sarkisyan
- Ajay Wasan

Second Paris Cs PV experiment: principle

- Excite 6S-7S transition in a vapour using **linearly polarised** laser **pulses** in a **longitudinal** E-field (16 kV/8 cm)
- Probe the 7S state using **stimulated emission** of a linearly-polarised probe beam exciting the 7S-6$P_{3/2}$ transition at 1.47 μm
- **Linear dichroism** causes rotation of the plane of polarisation (1 μrad) that reverses when the E-field is switched
- Balanced polarimeter for **dark-field** detection
- Totally different systematic effects *cf.* previous expts.
- 7 reversals or differences to isolate PV effect

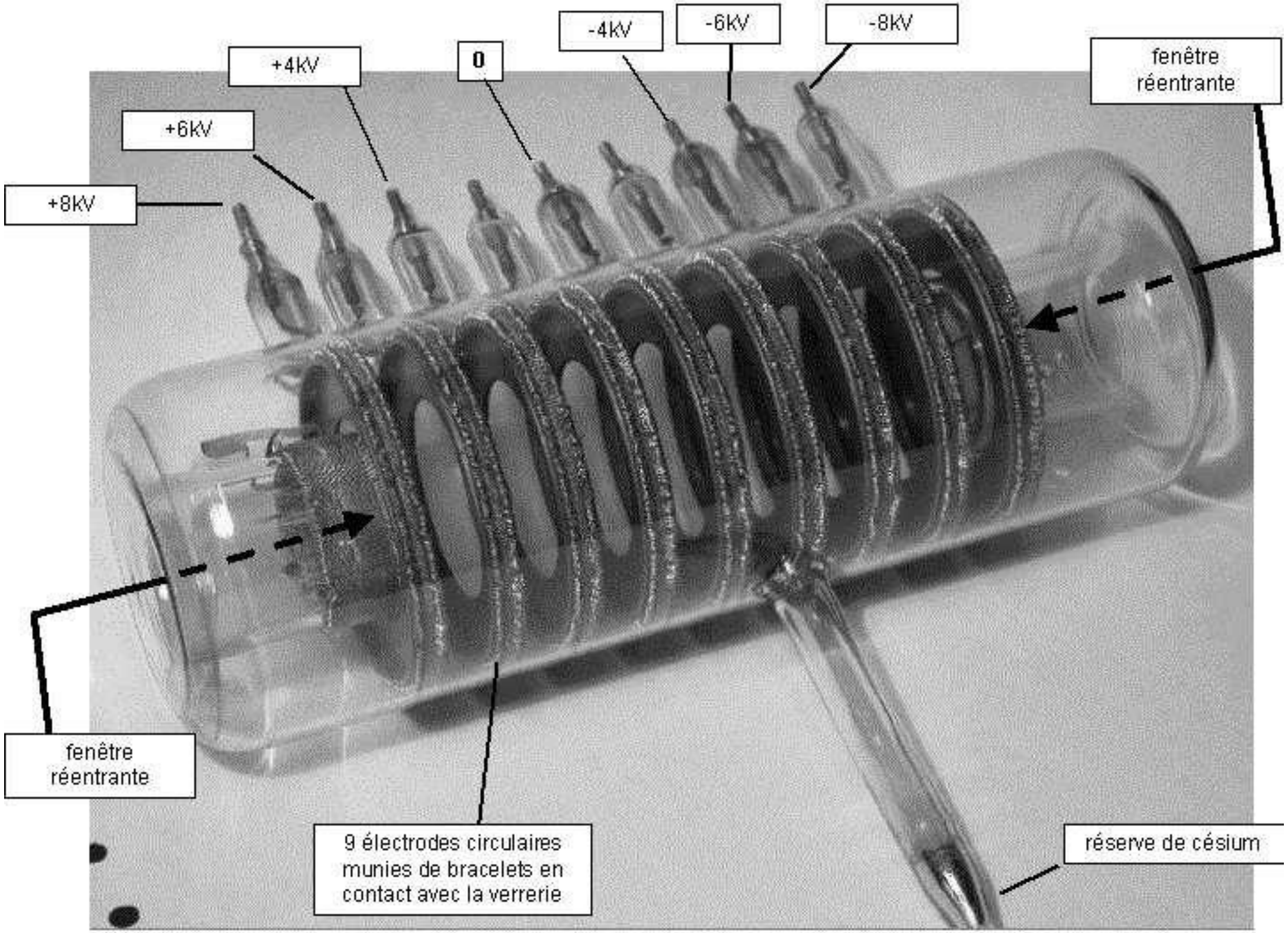


Experiment designed to achieve accuracy ~1% per hyperfine component and suited to 3-3’, 3-4’, 4-3’ and 4-4’



Probe
excitation
$\hat{\varepsilon}_{exc}$
$\hat{\varepsilon}_{pr}$
impulsions de référence
y
z
x
E_z
impulsion amplifiée
-45°
Cube séparateur de polarisation
+45°
Cs (10mTorr)
S_v
S_u

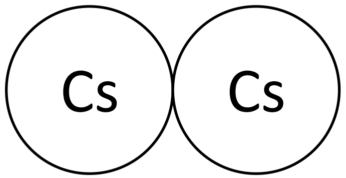
Cell used in the development of the experiment



Claude Bouchiat and the Paris Cs PV experiments

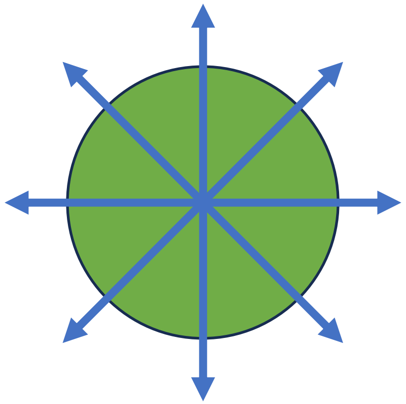
- Modelling of the E-field distribution in the Cs cells

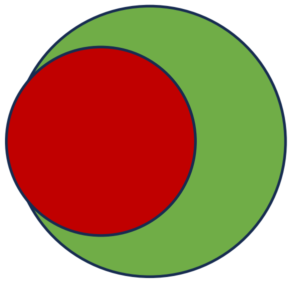
- Helped quantify troublesome molecular effect
- Green laser pulses photodissociate Cs dimers
- $Cs_2 + h\nu \rightarrow Cs(6S) + Cs(5D)$
- Then ionise one of the atoms



$Cs(5D) + h\nu \rightarrow Cs^+ + e$

Electrons accelerated by the longitudinal E-field ionise more molecules, creating a radial E-field – potential systematic!





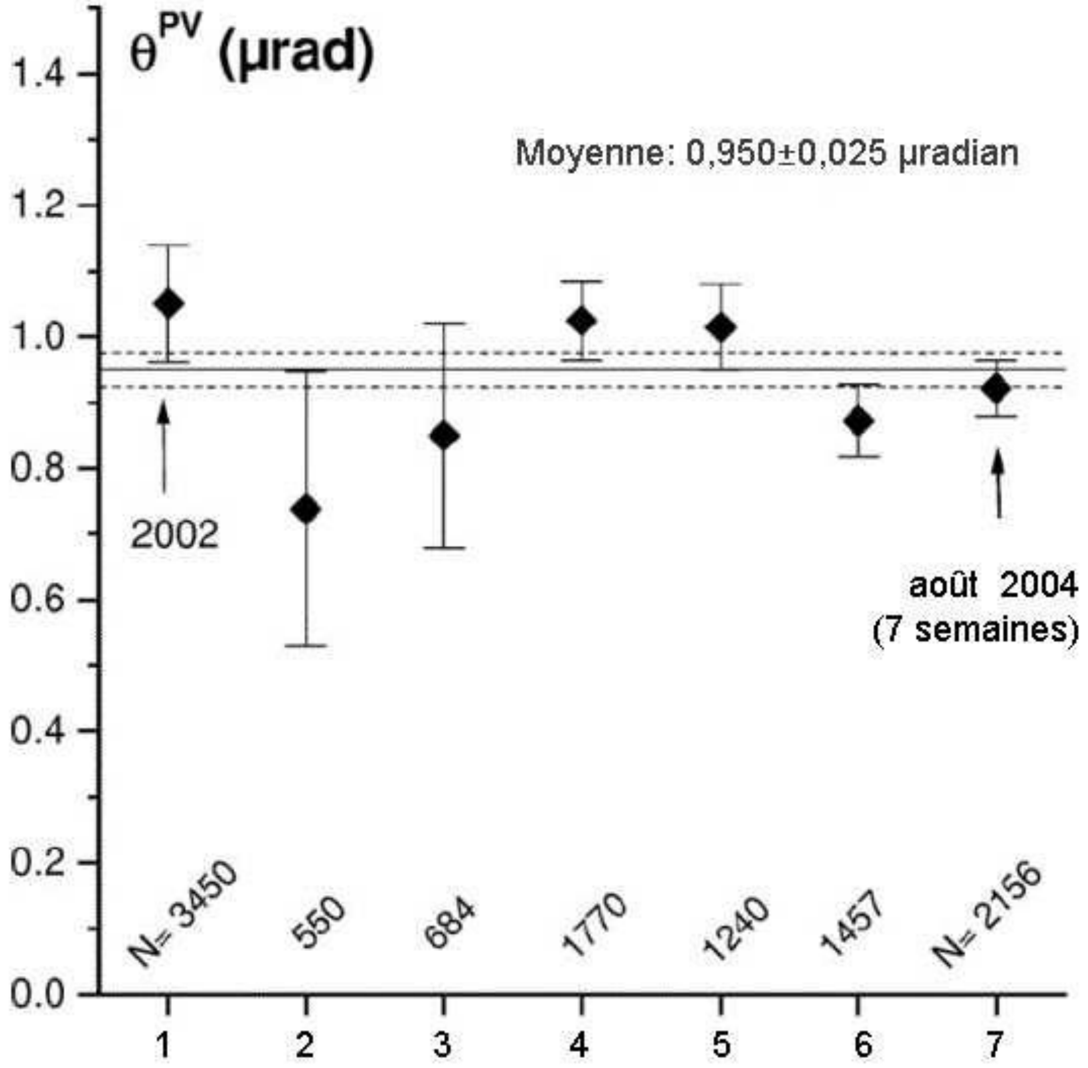
Heat cell to 250°C to dissociate dimers


Marie-Anne Bouchiat


Jocelyne Guéna
(1957-2019)


Michel Lintz

Results



Cs F=3$\longrightarrow$ F'=4

Statistical uncertainty limited by (available) integration time **2.6%**

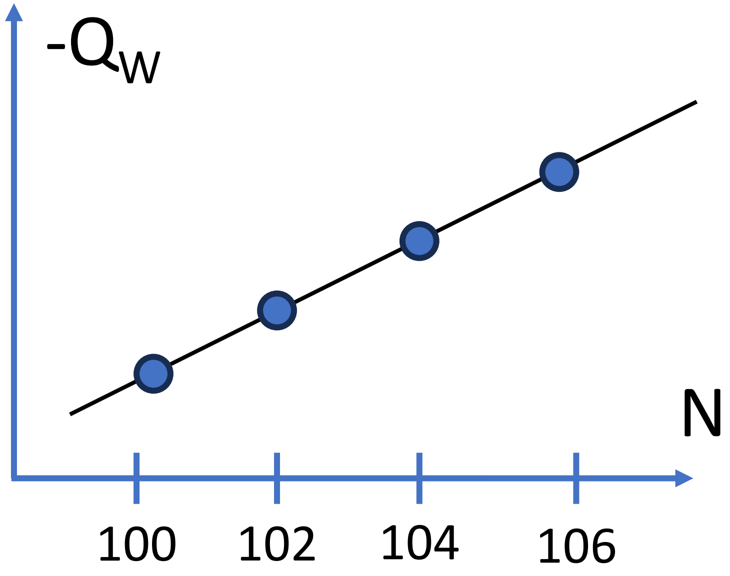
J. Guéna, M. Lintz, and M. A. Bouchiat *Phys. Rev. A* **71**, 042108 (2005)

Recent experiments and ongoing projects

- Yb (Dmitry Budker *et al.* Berkeley/Mainz)
- Z = 70 but PV effect = 100 × PV Cs

Studied a chain of isotopes, demonstrated the N-dependence of Q_W.

D. Antypas *et al.* *Nature Physics* **15**, 120-123 (2019)



- Fr Z=87 7S-8S (18 × PV Cs) in a magneto-optical trap

Radioactive, longest-lived isotope ^{223}Fr $t_{1/2}$ = 23 min

G. Gwinner and L.J. Orozco *Quantum Sci. Tech* **7**, 024001 (2022)

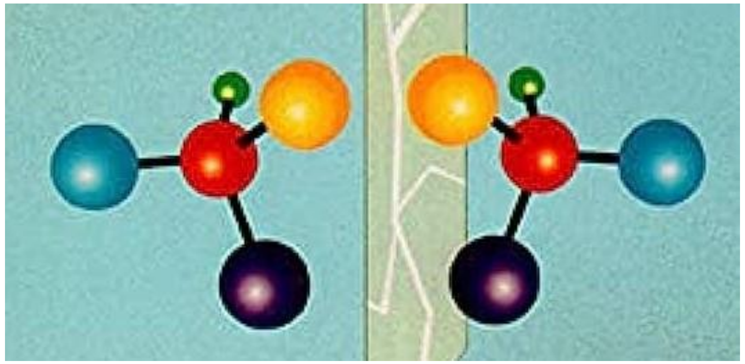
- Ra^+ Z=88 (50 × PV Cs) in a radio-frequency Paul trap

K. Jungmann *et al.* PANIC11 *AIP Conf. Proc.* **1441**, 552-554 (2012)

- Mirror-image molecules: $\Delta E/E < 2.5 \times 10^{-13}$ upper limit in CHFClBr

Project $Ru(acac)_3$, $Os(acac)_3$ acetylacetonate

M. Fiechter et al. *J. Phys. Chem. Lett.* **13**, 10011-10017 (2022)



Conclusion

- Atomic PV due to Z^0 exchange between electron and nucleus

- Claude and Marie-Anne Bouchiat showed the effect > Z^3 and suggested using weak optical transitions in heavy atoms

- Table-top particle physics experiments complementary to work with accelerators
  – constrain values of weak charges of quarks or θ_W

- PV experiments stimulate the development of atomic theory

- So far Q_w atomic PV experiments agree with Standard Model Q_w

- More PV experiments at the <1% uncertainty level most welcome

Merci de votre attention !