Lorentz invariance on trial in the weak decay of polarized atoms

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NWO
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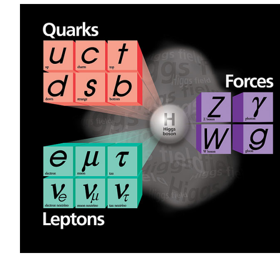
Lorentz Symmetry

Lorentz symmetry is a fundamental basis of

- **the theory of Special Relativity**
- **the Standard Model of Particle Physics**



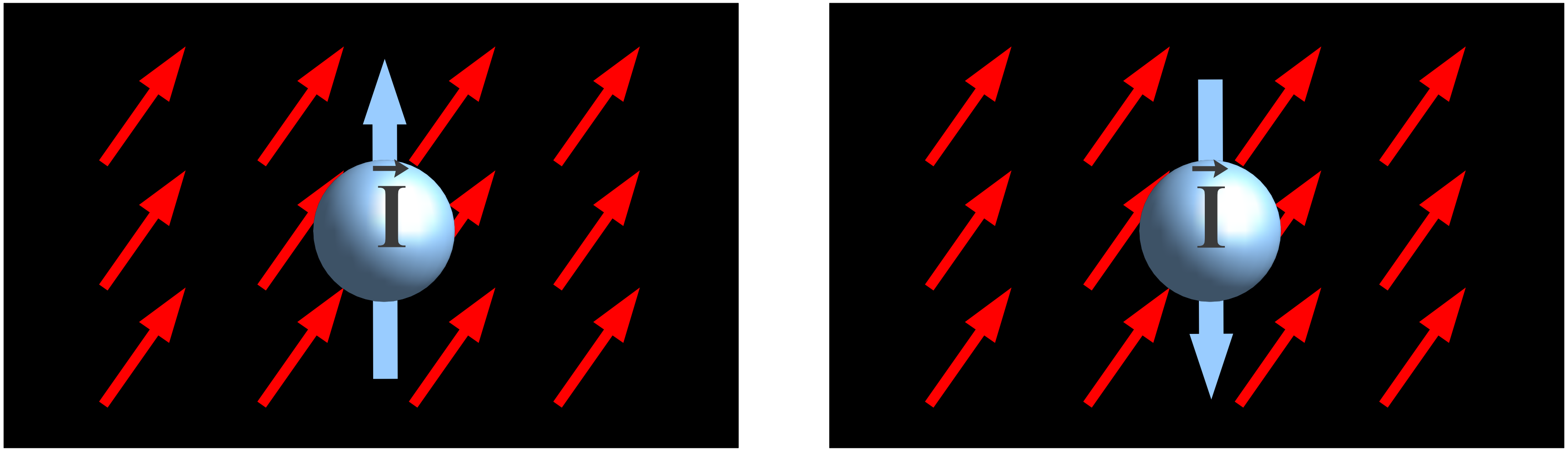
Connection to General Relativity and CPT symmetry

- **Lorentz symmetry breaking (LSB)**
  - Lorentz Symmetry spontaneously broken in Quantum Gravity models
  - "hidden" background fields ➞ preferred direction
  - precision experiments can look for signatures of LSB
- **Many experimental tests, no evidence of LSB**
  (mainly QED tests and gravity experiments)

Weak decay sector essentially unexplored!

Lorentz Symmetry Breaking

- assume nuclei interact with Lorentz-violating background fields



What is the change in the decay rate if the orientation of spin changes with respect to background fields?

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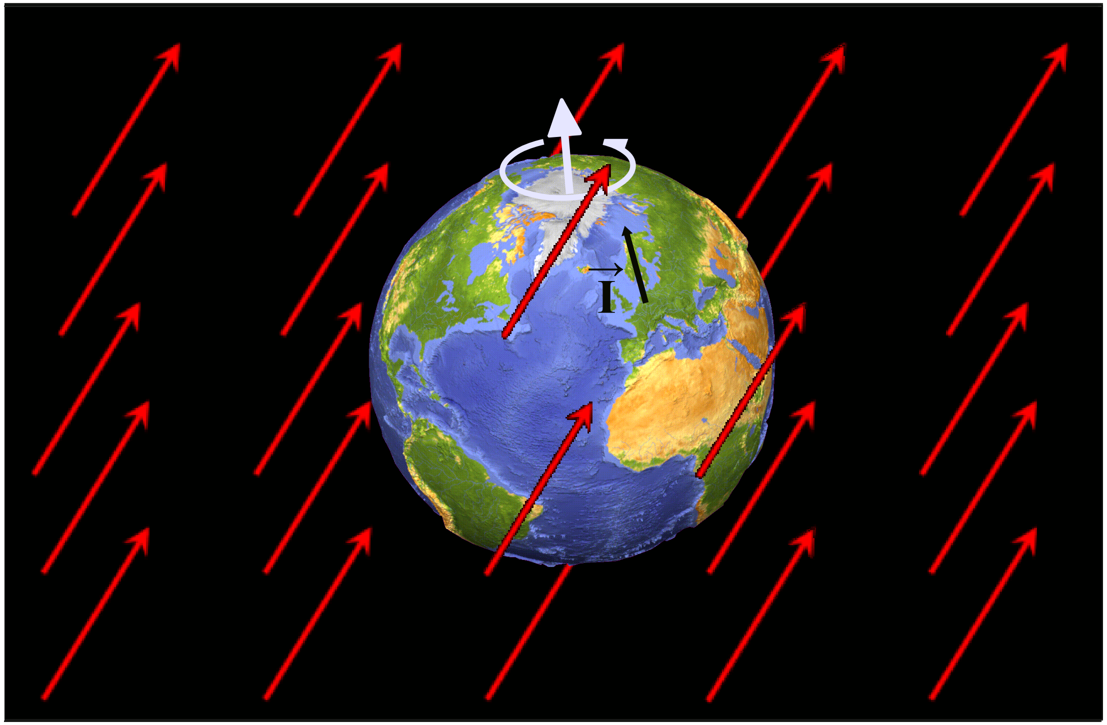

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*- search for variations induced by **daily**, yearly or "deliberate" reorientation of spin*

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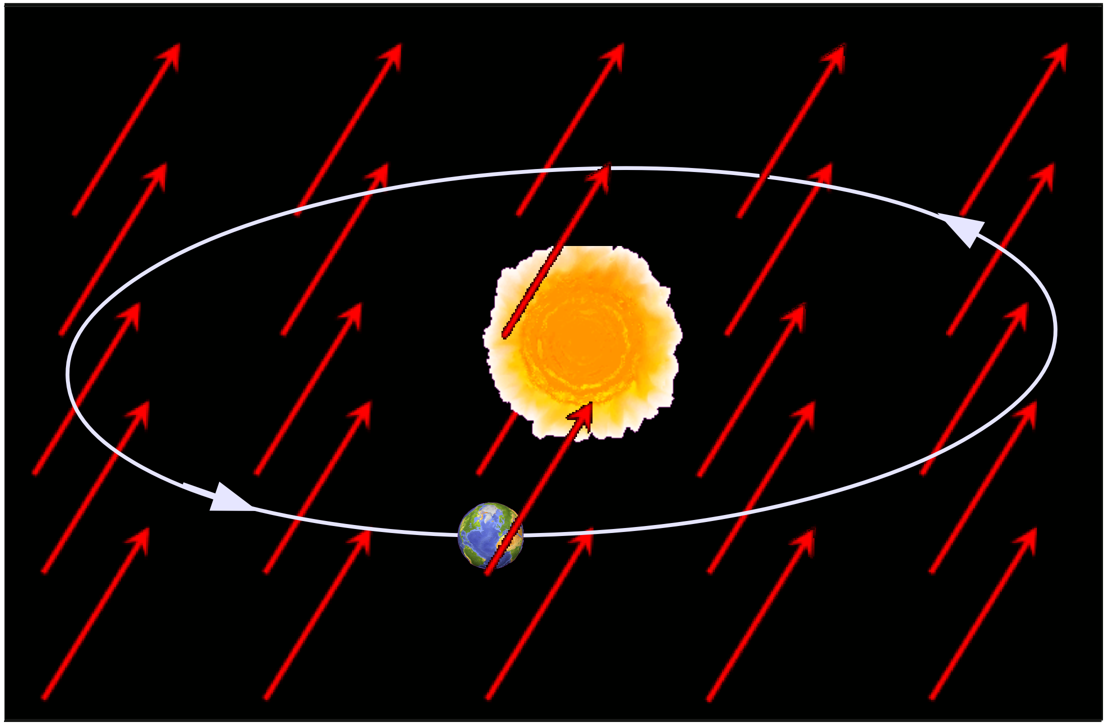

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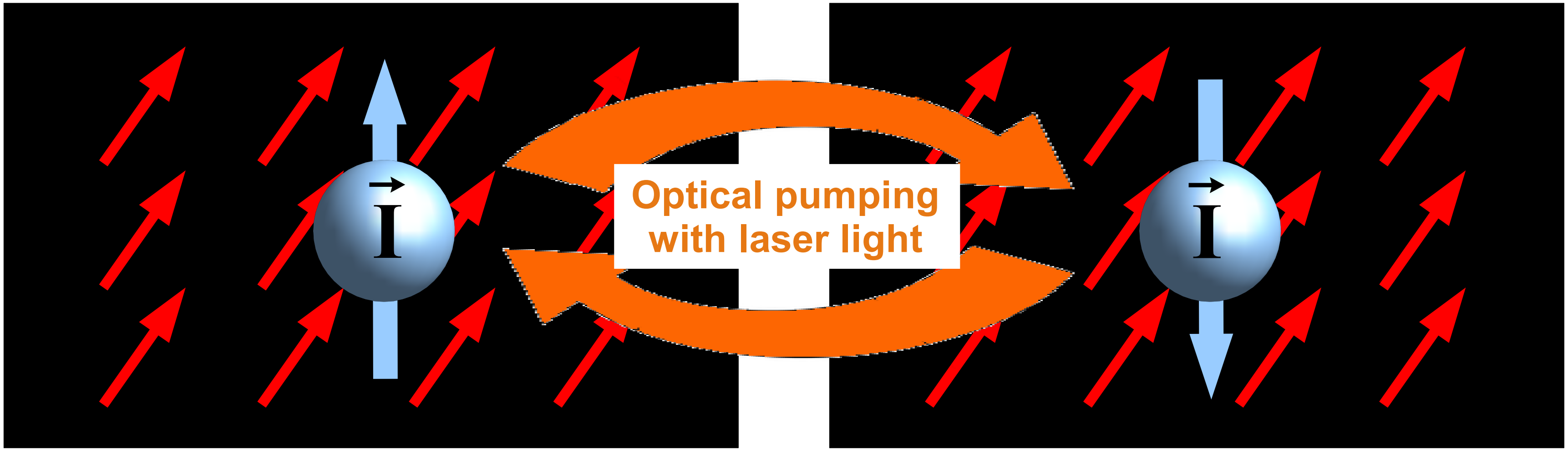

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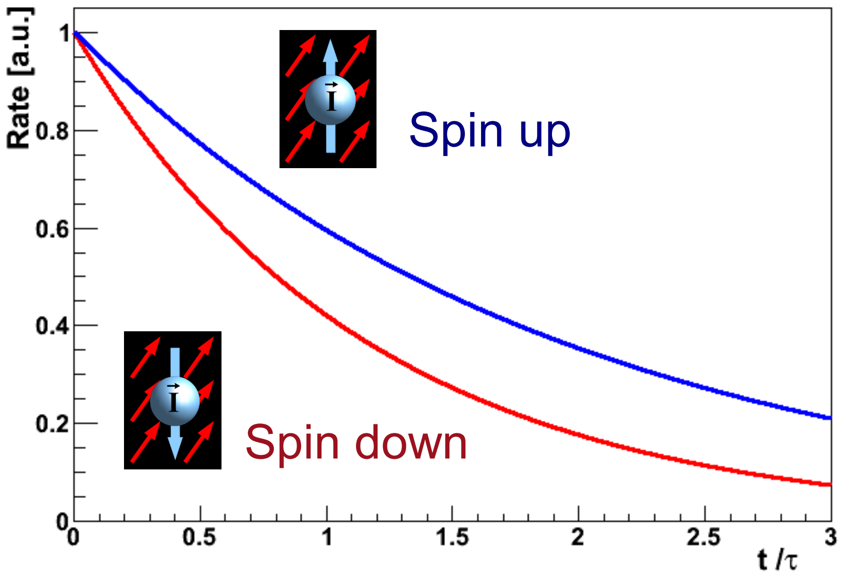
- search for variations induced by daily, yearly or ***"deliberate"*** *reorientation of spin*

Experiment:

- **Change in decay rate** for different polarization orientations:



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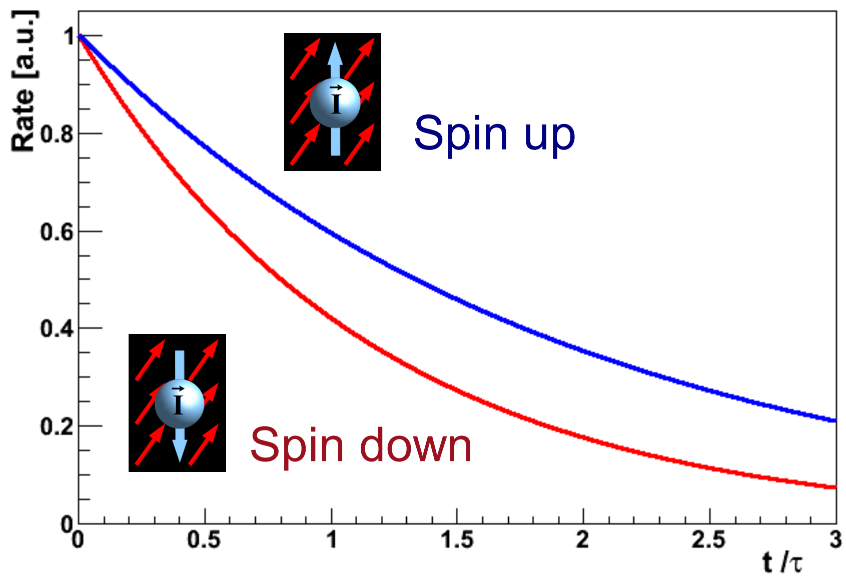

$$\frac{d\Gamma}{dE\, d\Omega} \sim \underbrace{\left(1 + A_0 \frac{\langle \vec{I} \rangle}{I} \cdot \frac{\vec{p}}{E}\right)}_{\text{SM}} + \xi_1 \left(1 + \xi_A \left(\hat{p} \cdot \frac{\langle \vec{I} \rangle}{I}\right)\right) \hat{p}\, \hat{n} + \xi_2 \frac{\langle \vec{I} \rangle}{I} \hat{n} + \xi_3\, \hat{p}_i \left(\frac{\langle \vec{I} \rangle}{I}\right)_j \rho^{ij}$$

I = nuclear spin; p, E = electron momentum and energy

$\xi_{1,2,3,A}$ = coupling strength to LIV fields $\hat{n}$, ρ^{ij}

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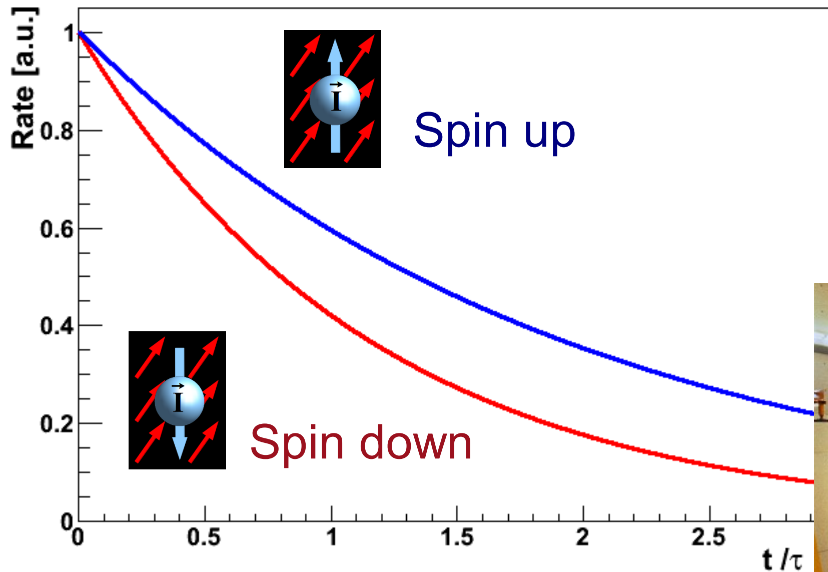
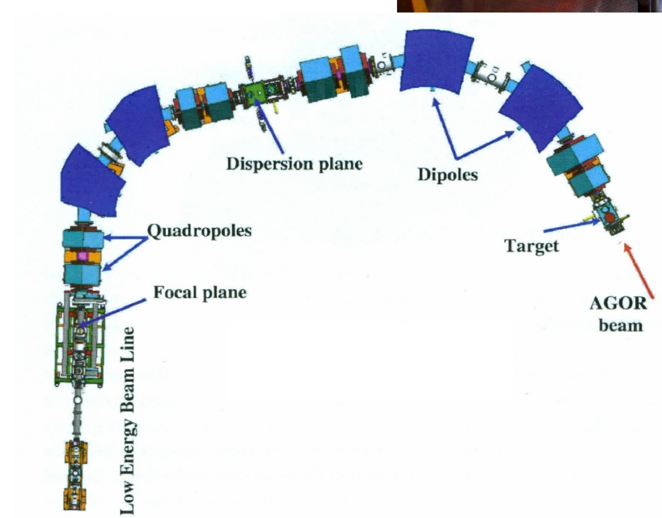


- **AGOR cyclotron at KVI**

  Produce short-lived isotopes

- **TRIμP isotope separator**

  Clean isotope beam

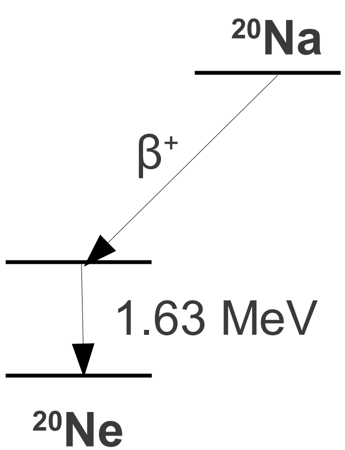


^{20}Na:

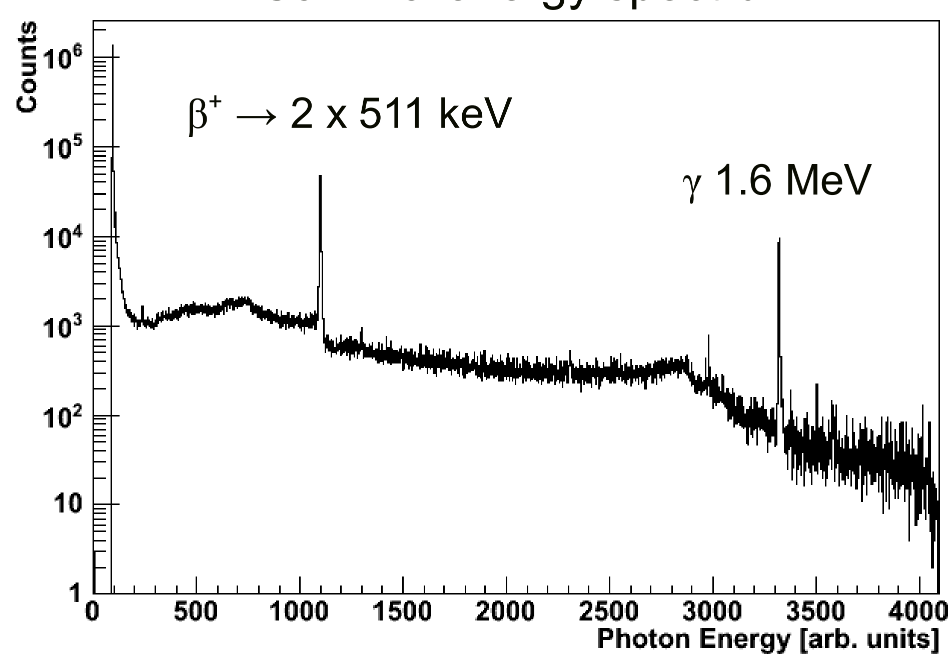
Choice of ^{20}Na:

- **Properties**: $2^+ \rightarrow 2^+$ (GT), β^+, $\tau_{1/2}$ = 0.448s, β-asymmetry parameter A_0=1/3
- **Produced** via $^{20}Ne + p \rightarrow {}^{20}Na + n$ reaction: 10^6 decays/s
- **80% decay** to excited state of ^{20}Ne(1.63 MeV)

Level scheme

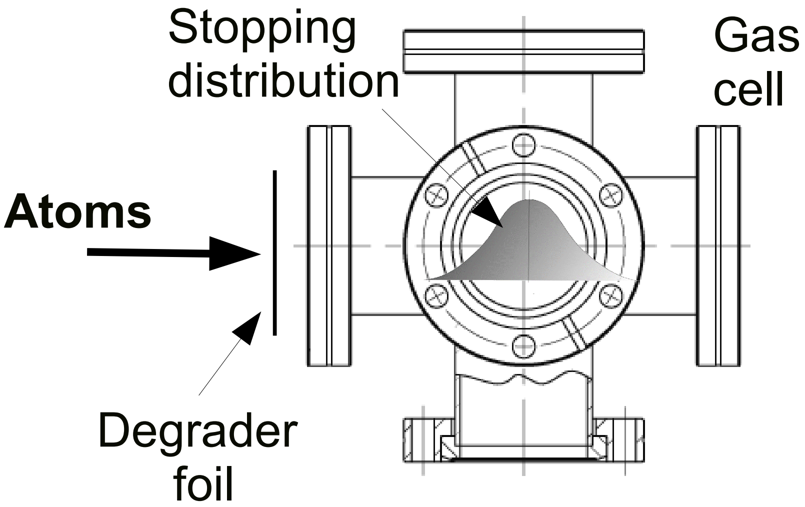


Gamma-energy spectrum



Experiment:

- **Isotope beam stopped** in buffer gas cell
  - Aluminum foil degraders & buffer gas pressure (noble gas, 2atm)



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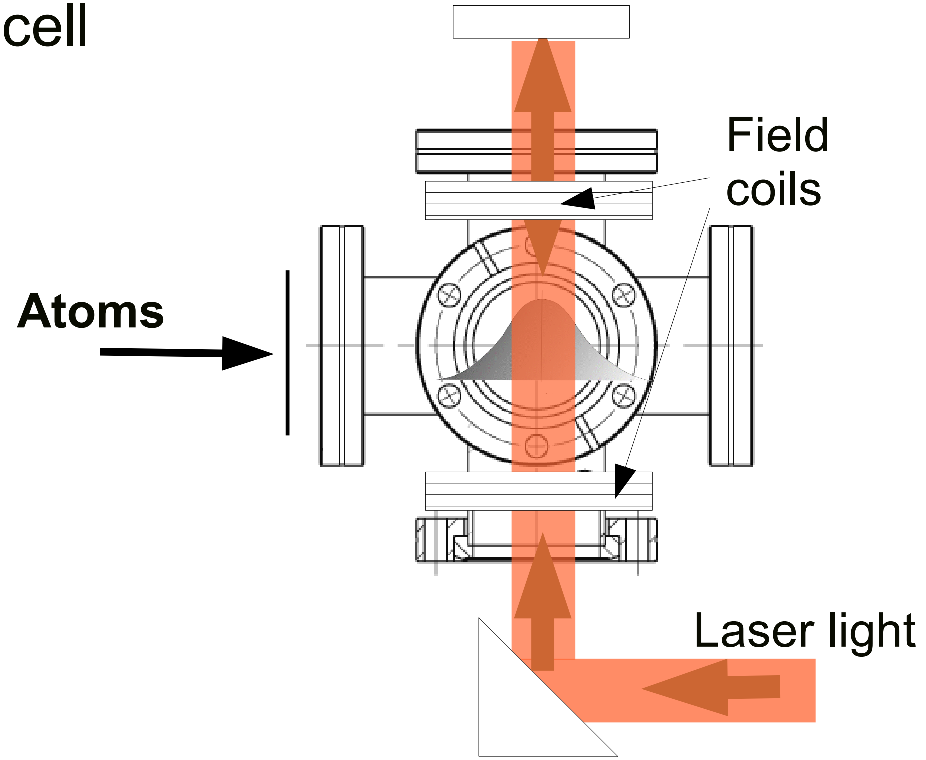

- **Polarized nuclei** via optical pumping:
  - magnetic holding field
  - circularly polarized $\sigma^{\pm}$ light

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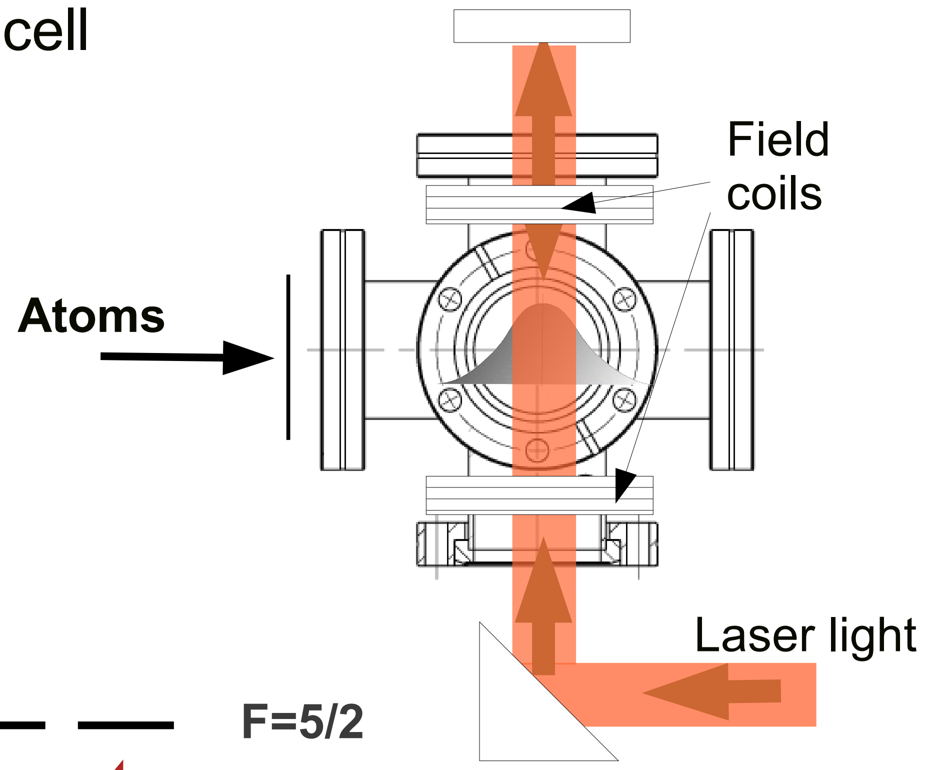

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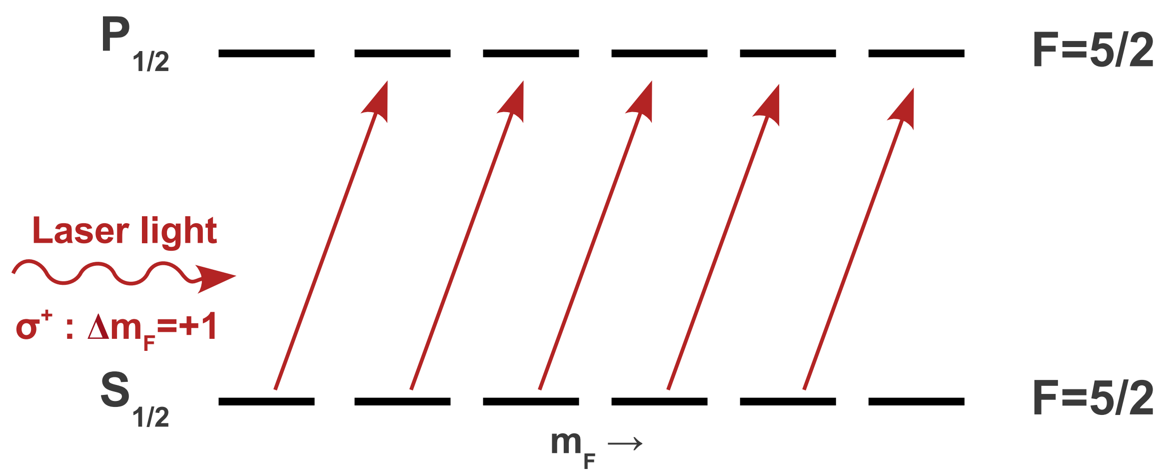

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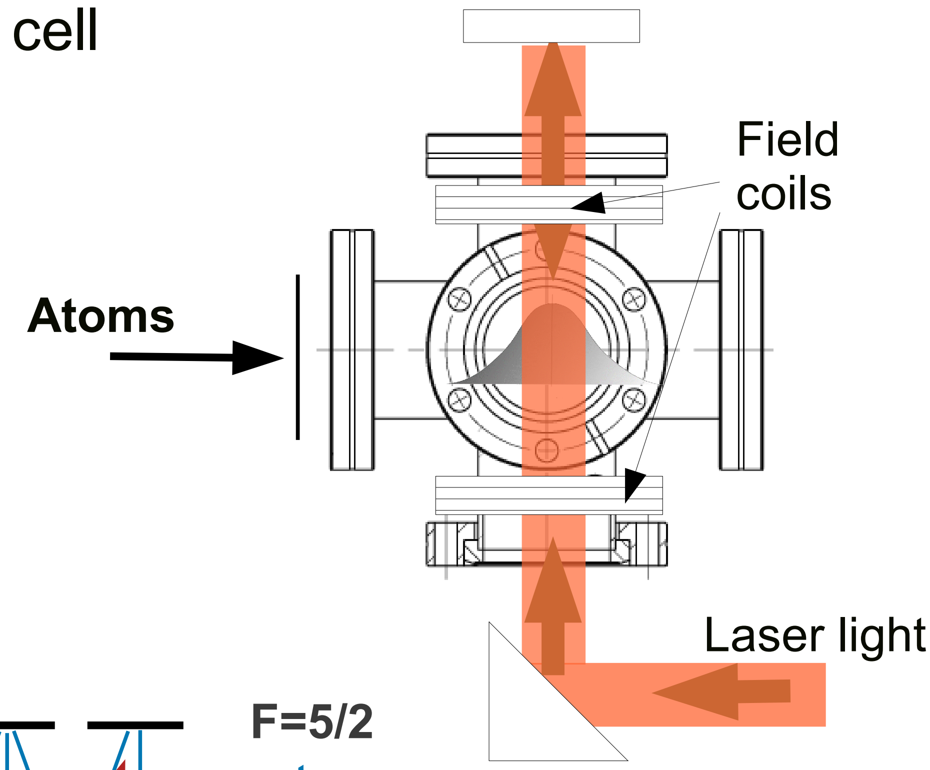

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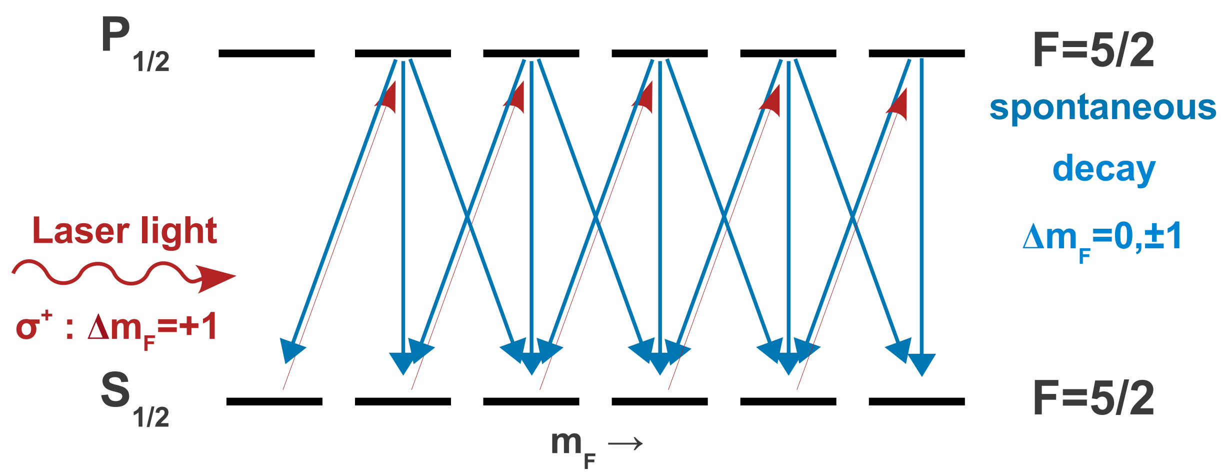

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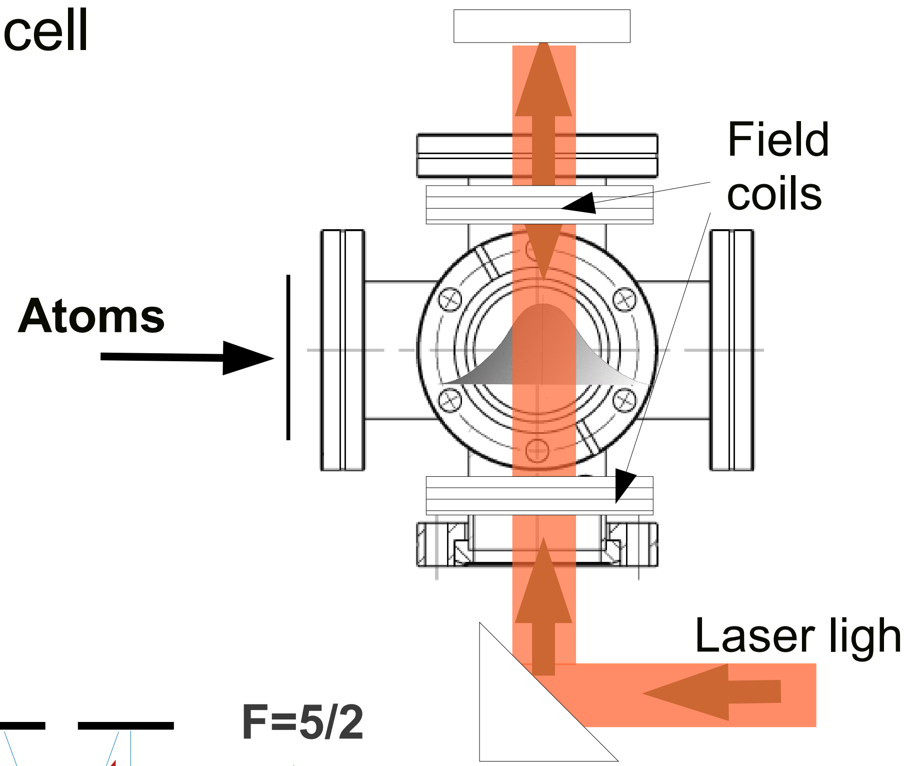

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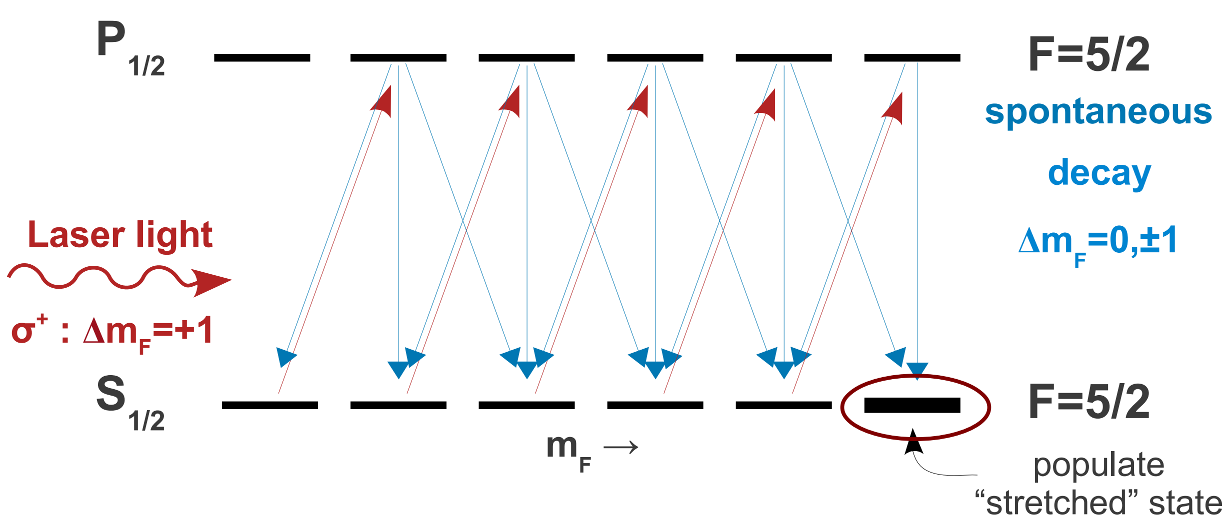

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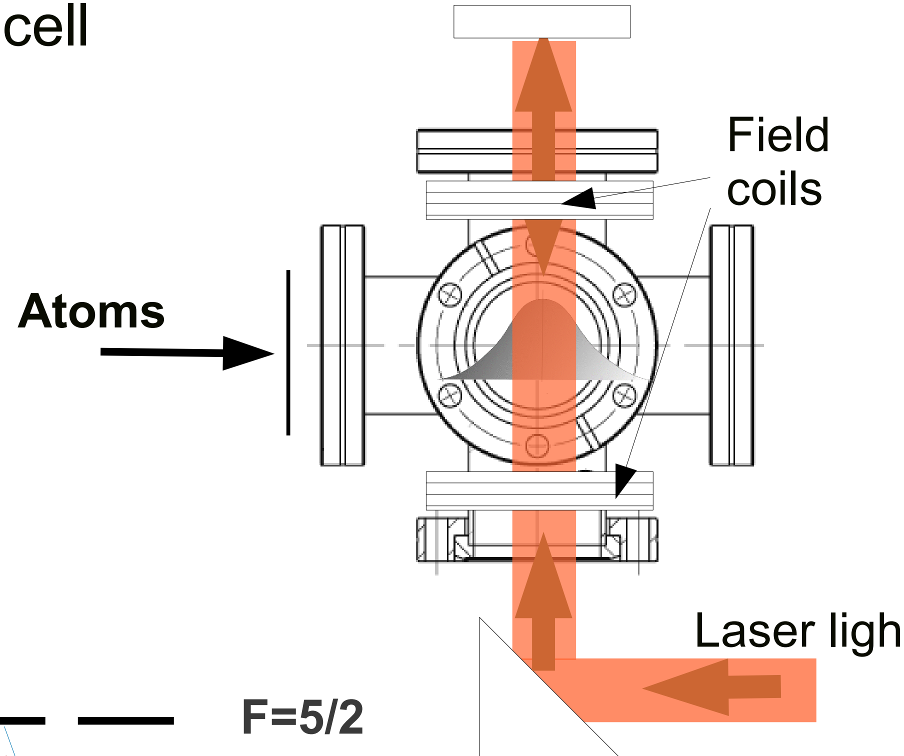

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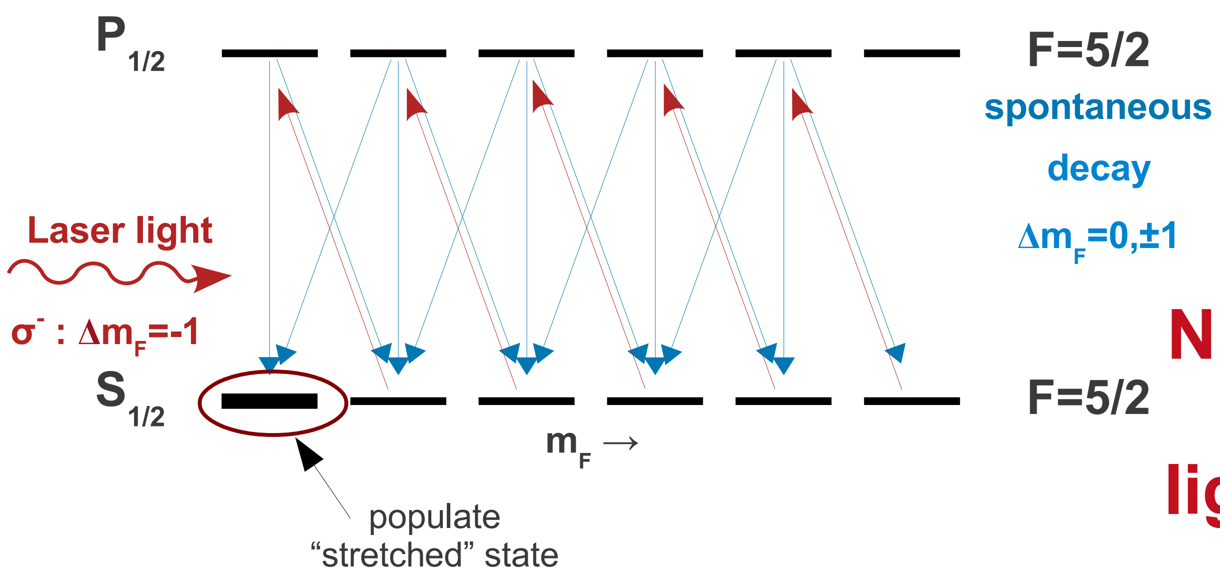
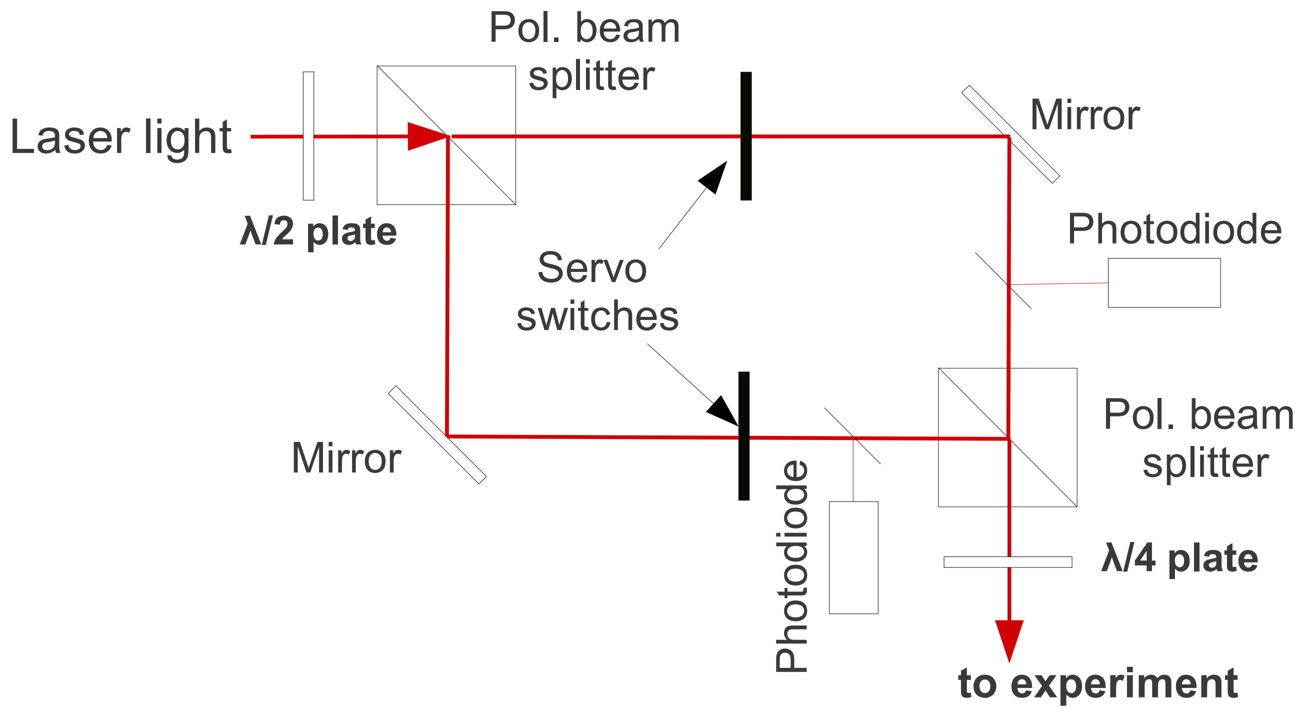


Nuclear spin follows light helicity

Experiment:

- **Isotope beam stopped** in buffer gas cell
  - Aluminum foil degraders & buffer gas pressure (noble gas, 2atm)

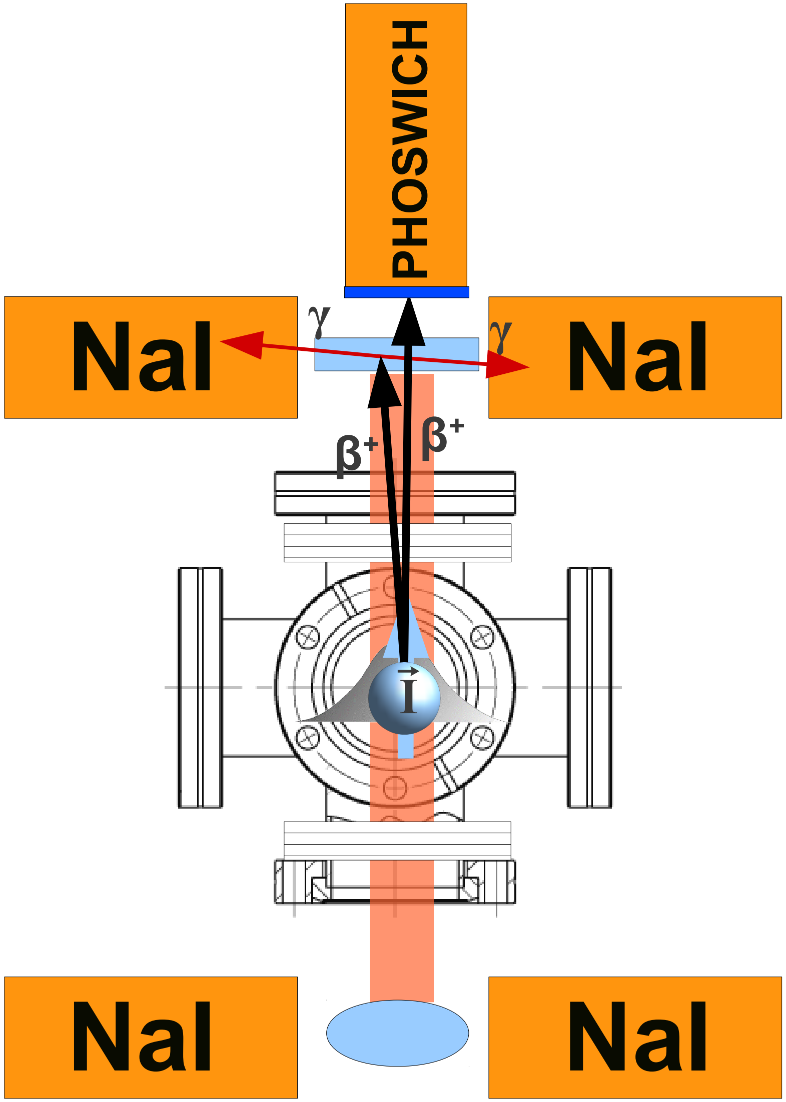
- **Polarized nuclei** via optical pumping:
  - Switching polarization:



Measurement of polarization:

- **PHOSWICH detector** above target cell to detect β^+
- **Two pairs of NaI detectors** to measure 511 keV coincidences from β^+ particles stopped in mirrors above and below target cell

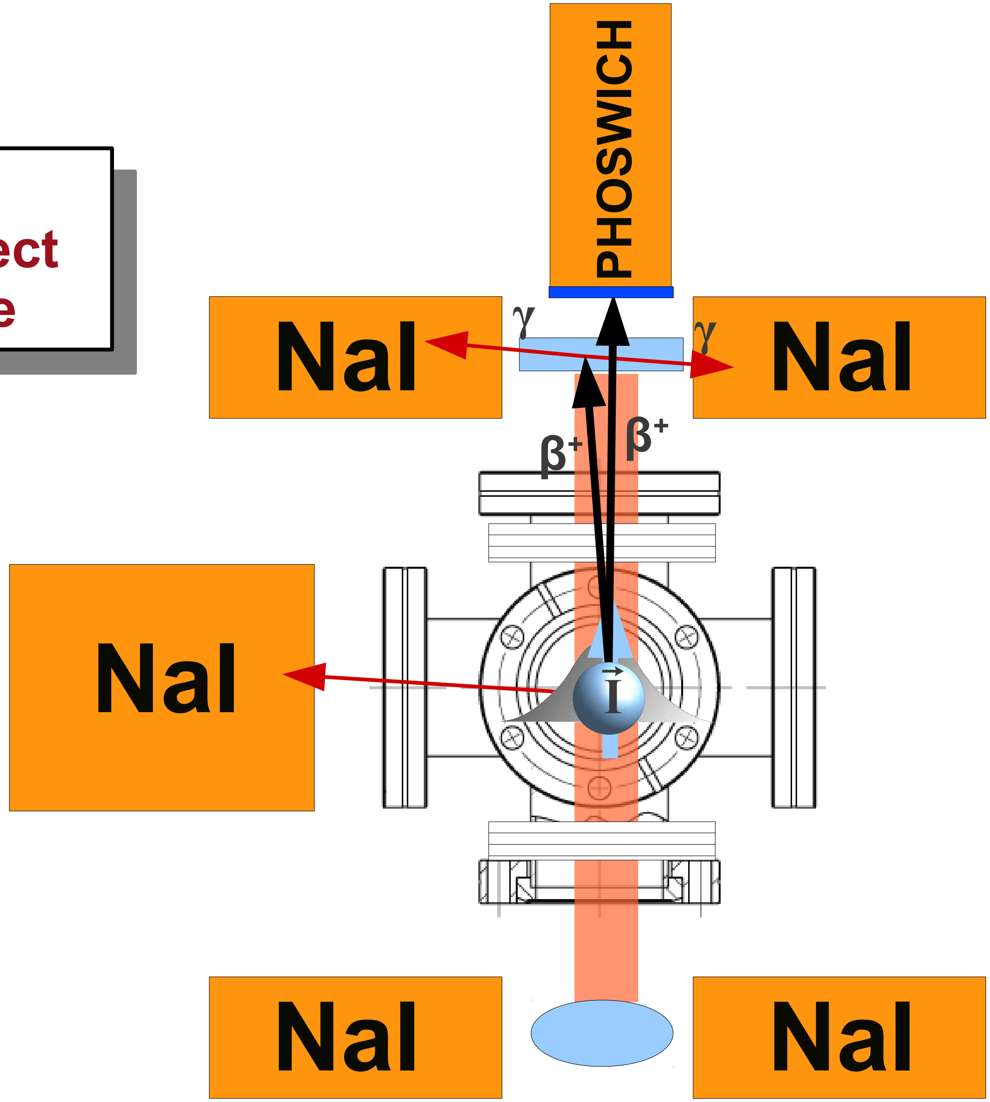
Use parity violating decay asymmetry of weak interaction to monitor nuclear polarization



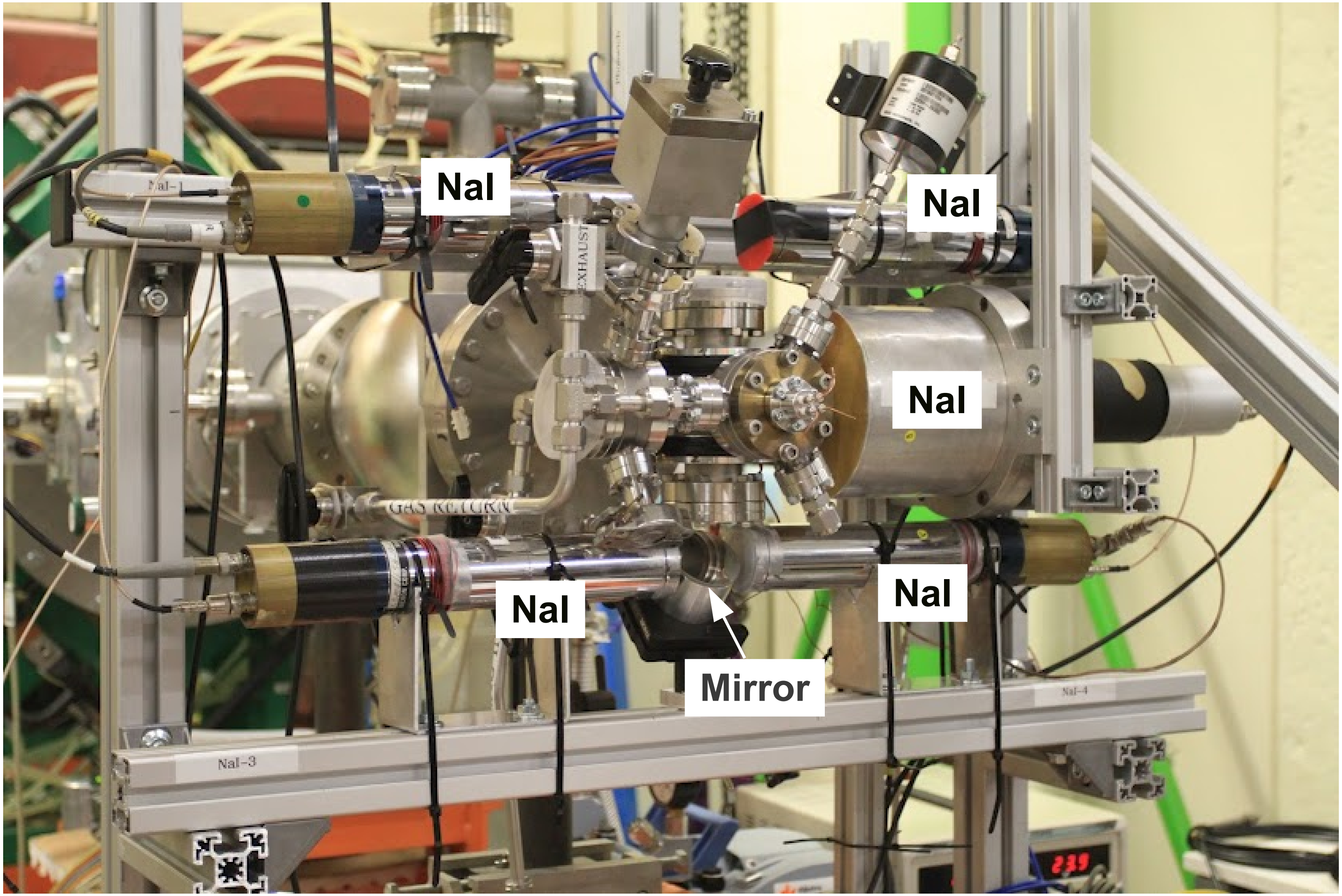
Measurement of lifetime:

- **Additional NaI detector** for daughter particles decay photons
  $2^+ \rightarrow 0^+$ EM-decay of ^{20}Ne, parity conserving, Lorentz invariant

Use EM decay of ^{20}Ne daughter nucleus to detect changes in ^{20}Na lifetime

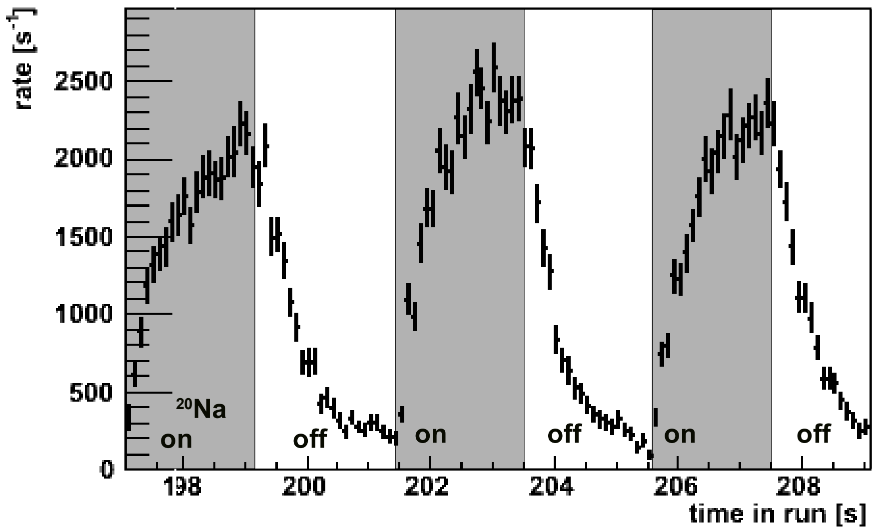


Experimental setup:



Polarization measurement:

- **β⁺ Rates** from PHOSWICH detector
  - 2s-on, 2s-off period of ^{20}Na beam:



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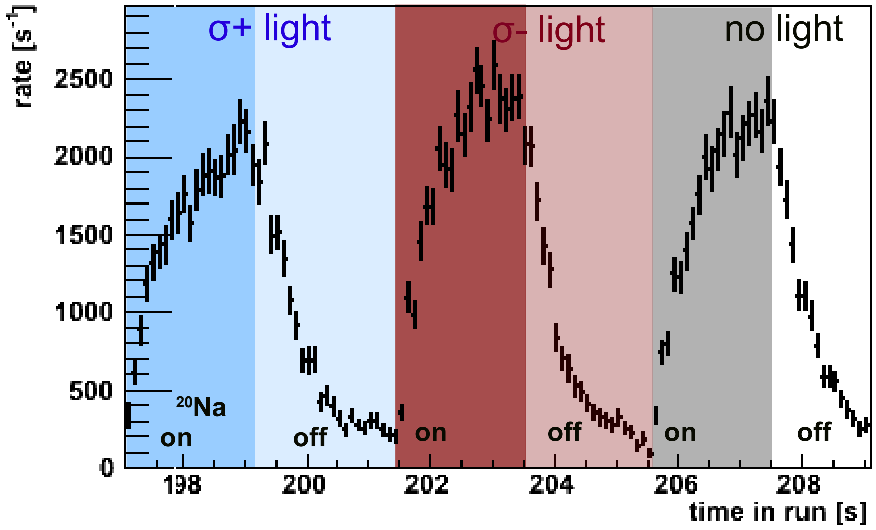

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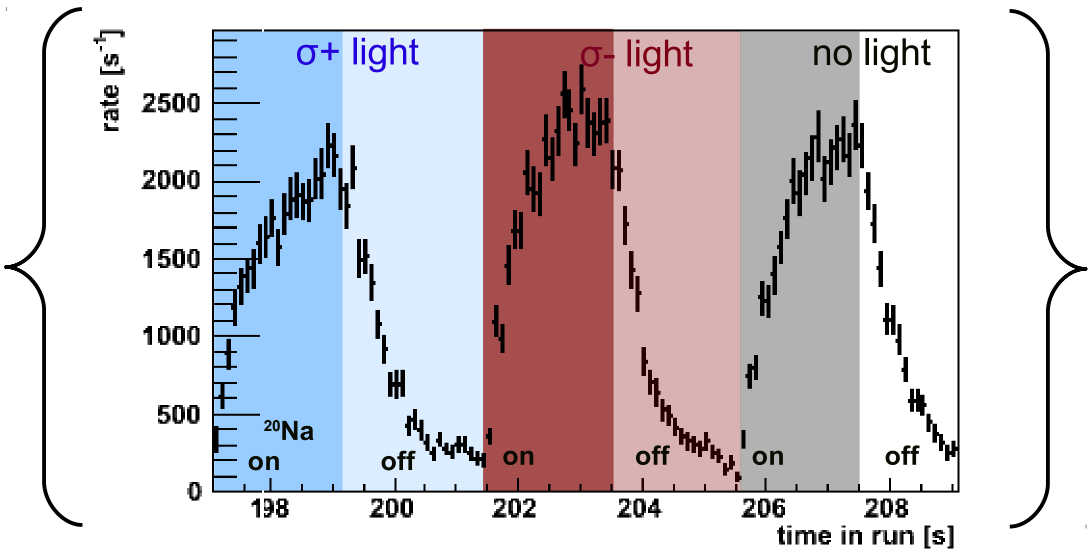

n

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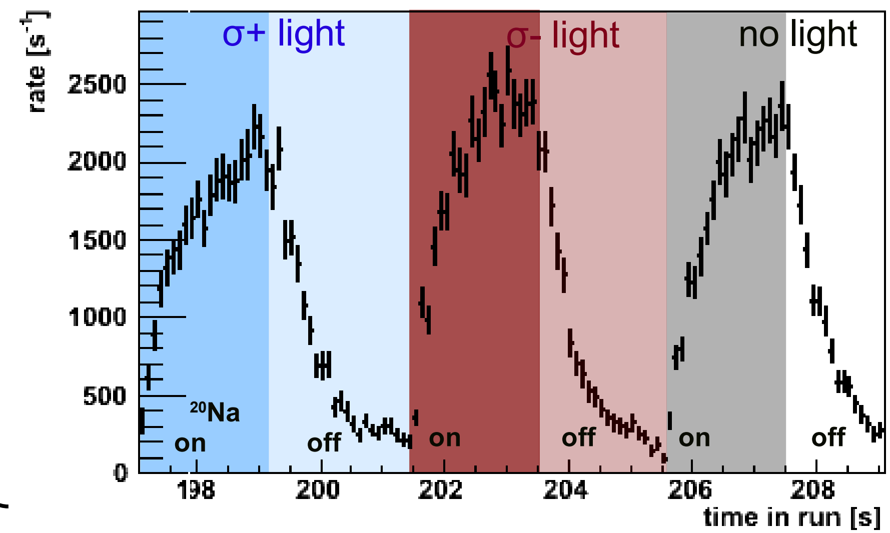
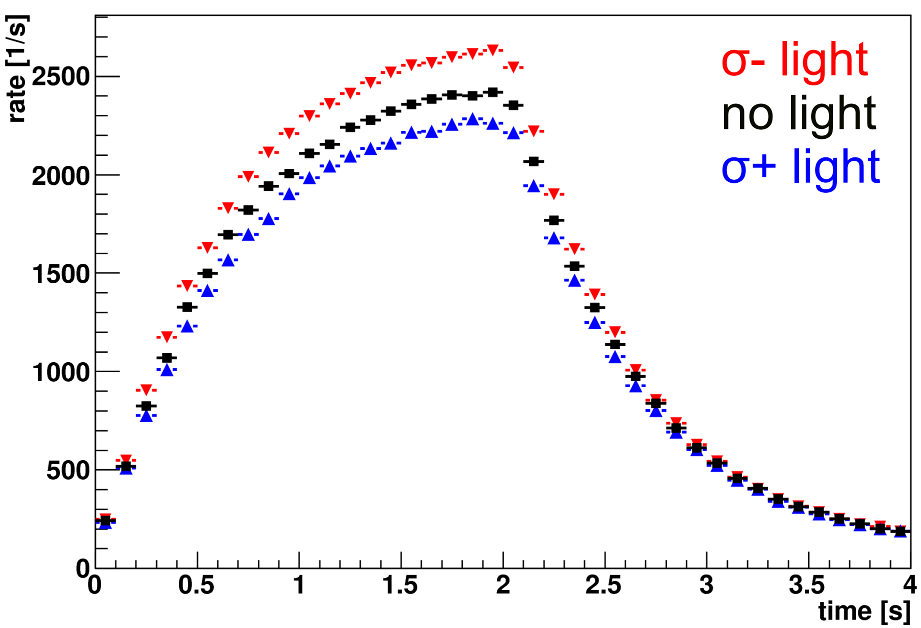
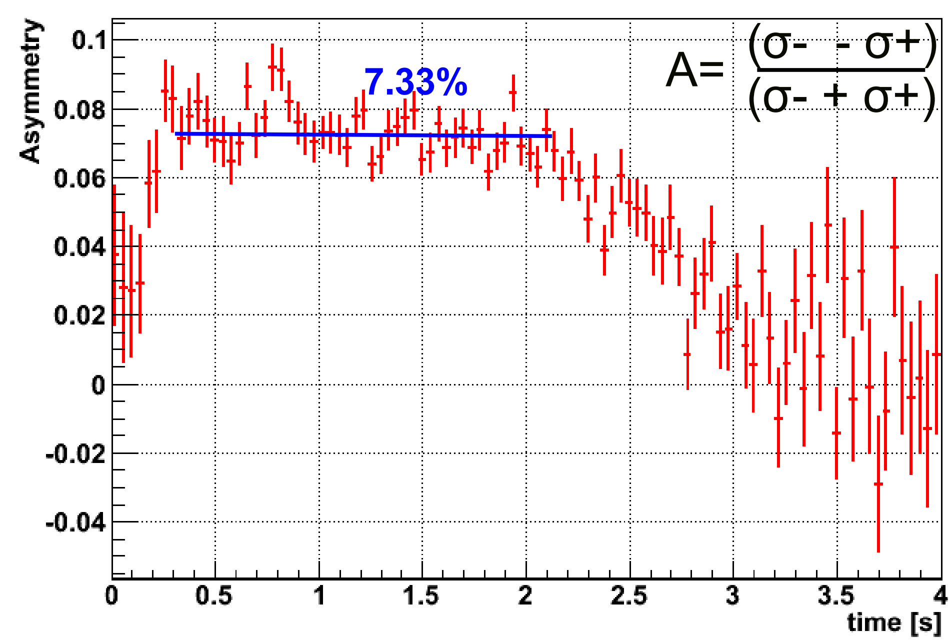
n







Lifetime measurement:

- γ **Rates** from NaI detector
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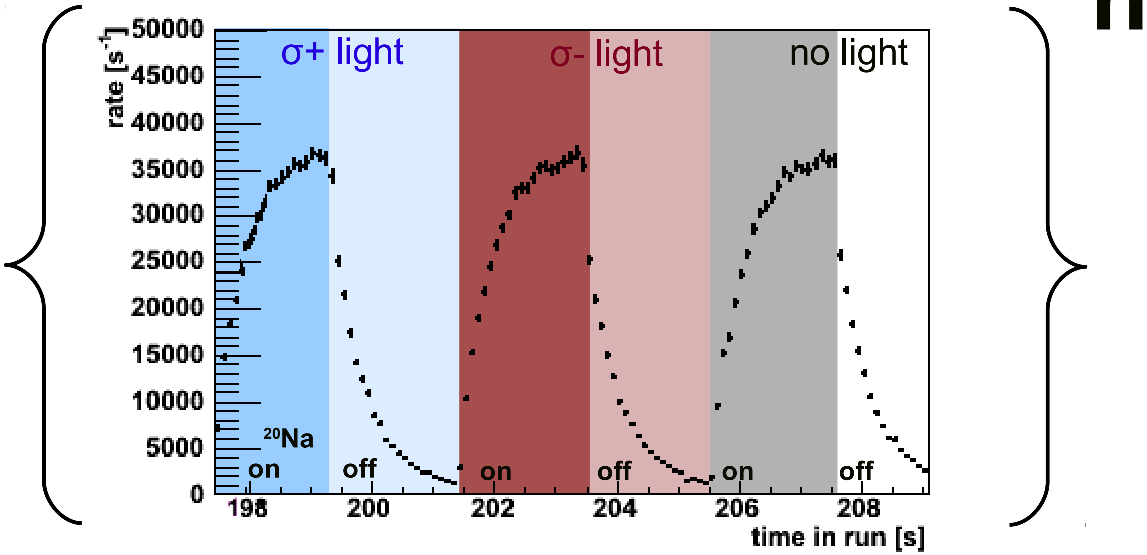

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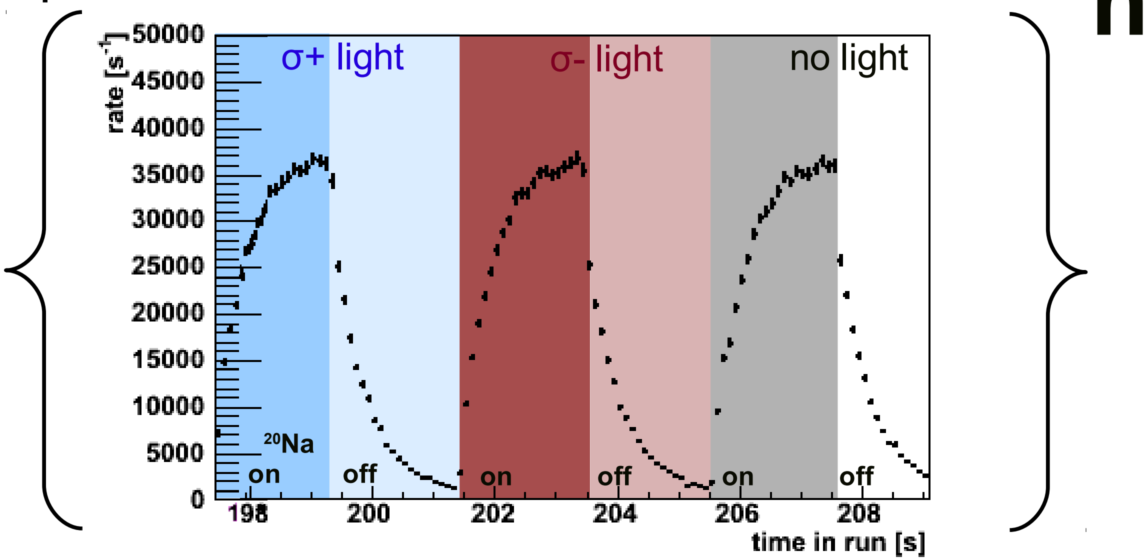
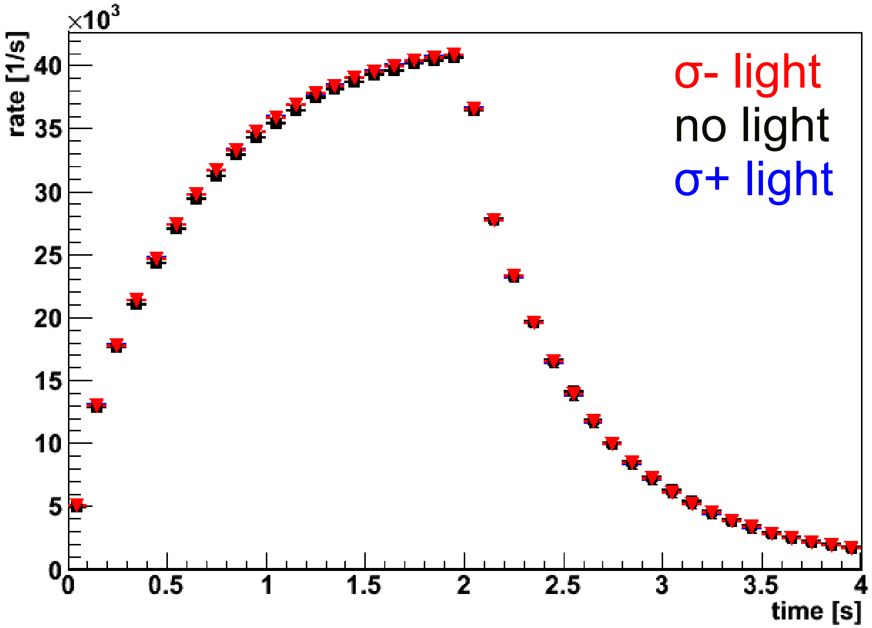
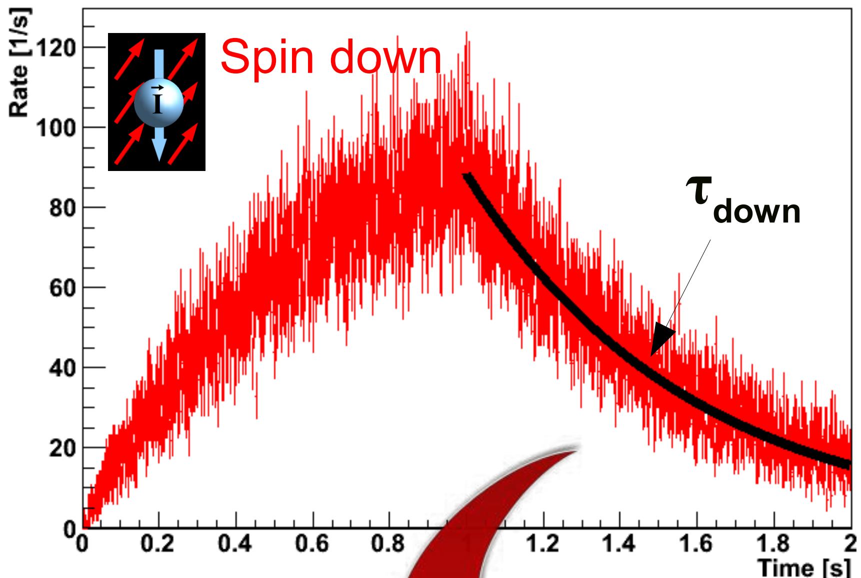


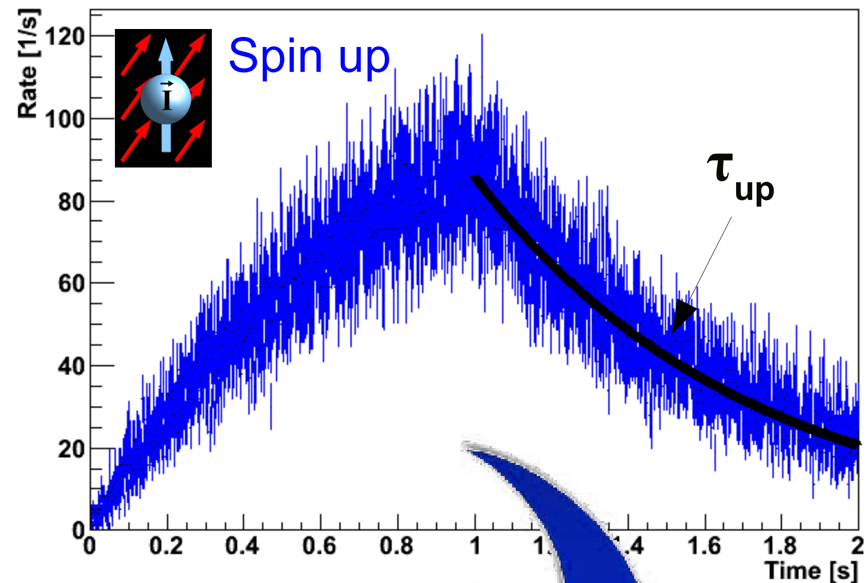


Lifetime-analysis:

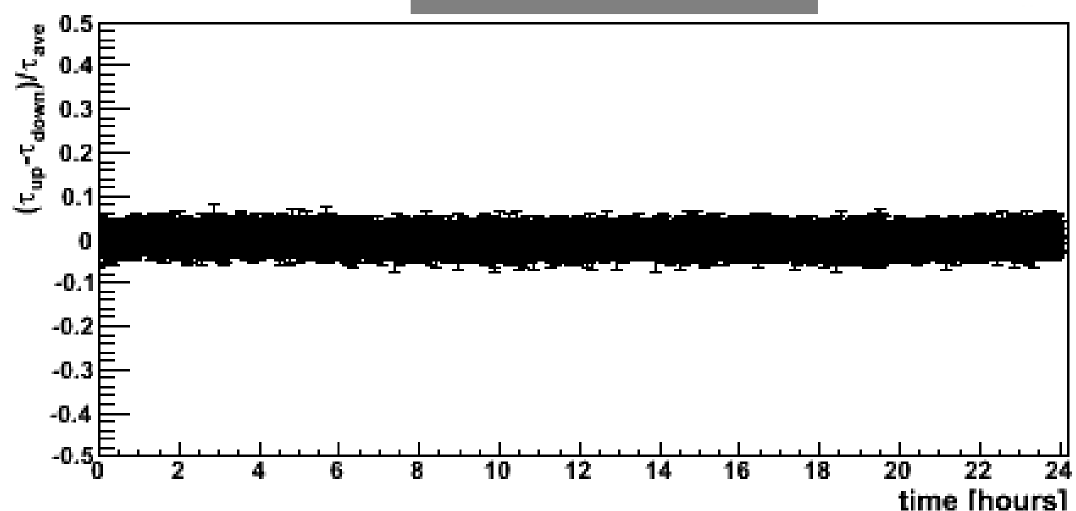
- *compare lifetimes for σ+ and σ- case*
- *take into account time-dependence of polarization*
- *define and estimate systematic effects*
- *train algorithms on "no light" case*

Data Analysis (simulation):





$$\Delta = \frac{\tau_{up} - \tau_{down}}{\tau_{ave}}$$



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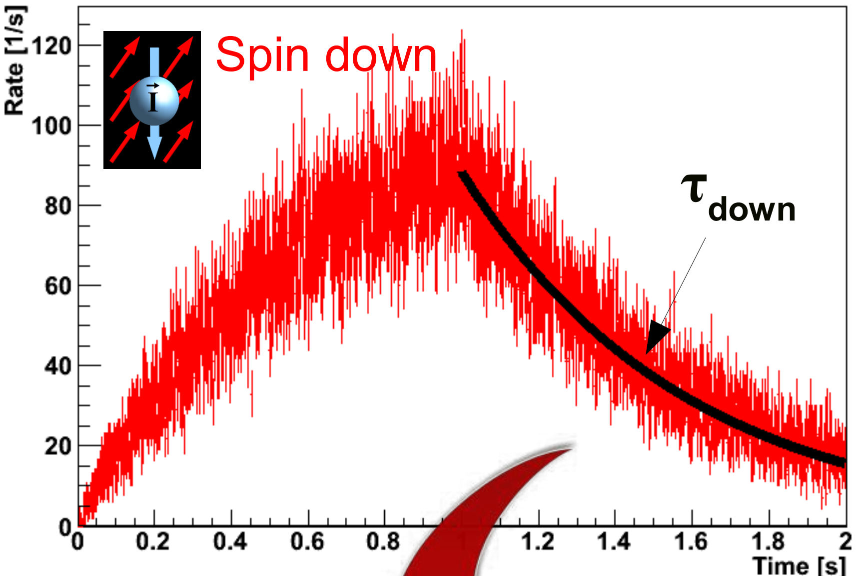
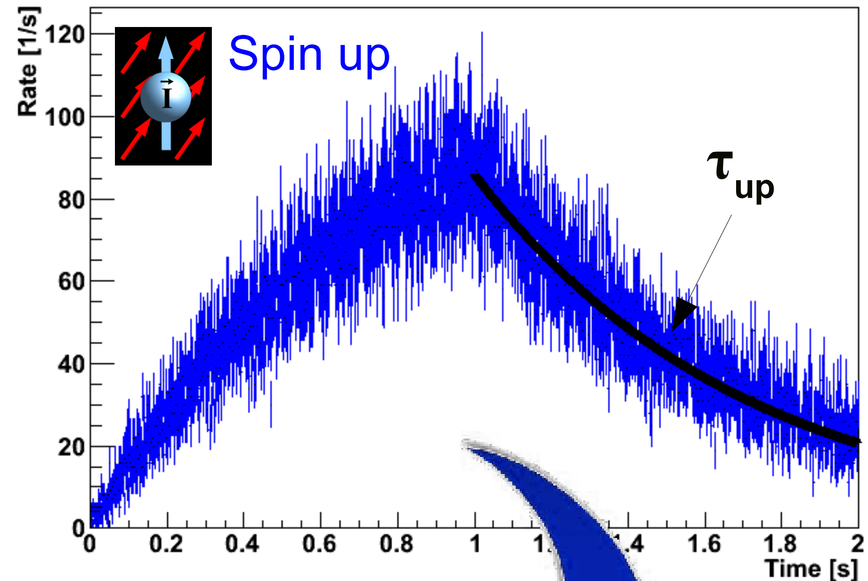


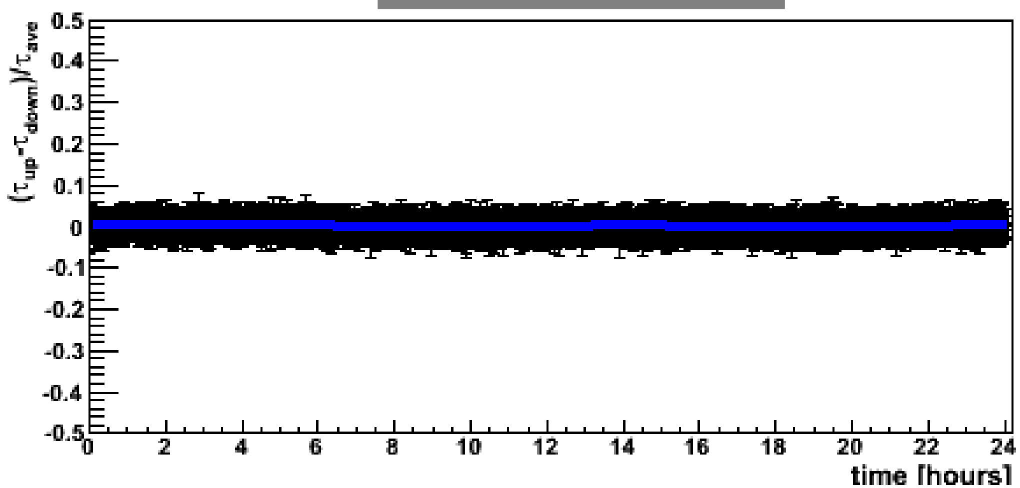


$$\Delta = \frac{\tau_{up} - \tau_{down}}{\tau_{ave}}$$

Fitfunction:

$$\Delta(t) = C + A_s \sin(\omega_\oplus t) + A_c \cos(\omega_\oplus t) + B_s \sin(2\omega_\oplus t) + B_c \cos(2\omega_\oplus t)$$

$$\omega_\oplus = 2\pi / T_{\text{sid. day}}$$



From fit:

$C = (0.84 \pm 1.31) \times 10^{-4}$

$A_S = (14.9 \pm 1.85) \times 10^{-4}$

$A_C = (13.6 \pm 1.85) \times 10^{-4}$

$B_S = (20.3 \pm 1.85) \times 10^{-4}$

$B_C = (0.69 \pm 1.85) \times 10^{-4}$

Data Analysis:

Analyzing 24h of non-polarized events:

- fit lifetimes of 2 consecutive “no-light”-periods

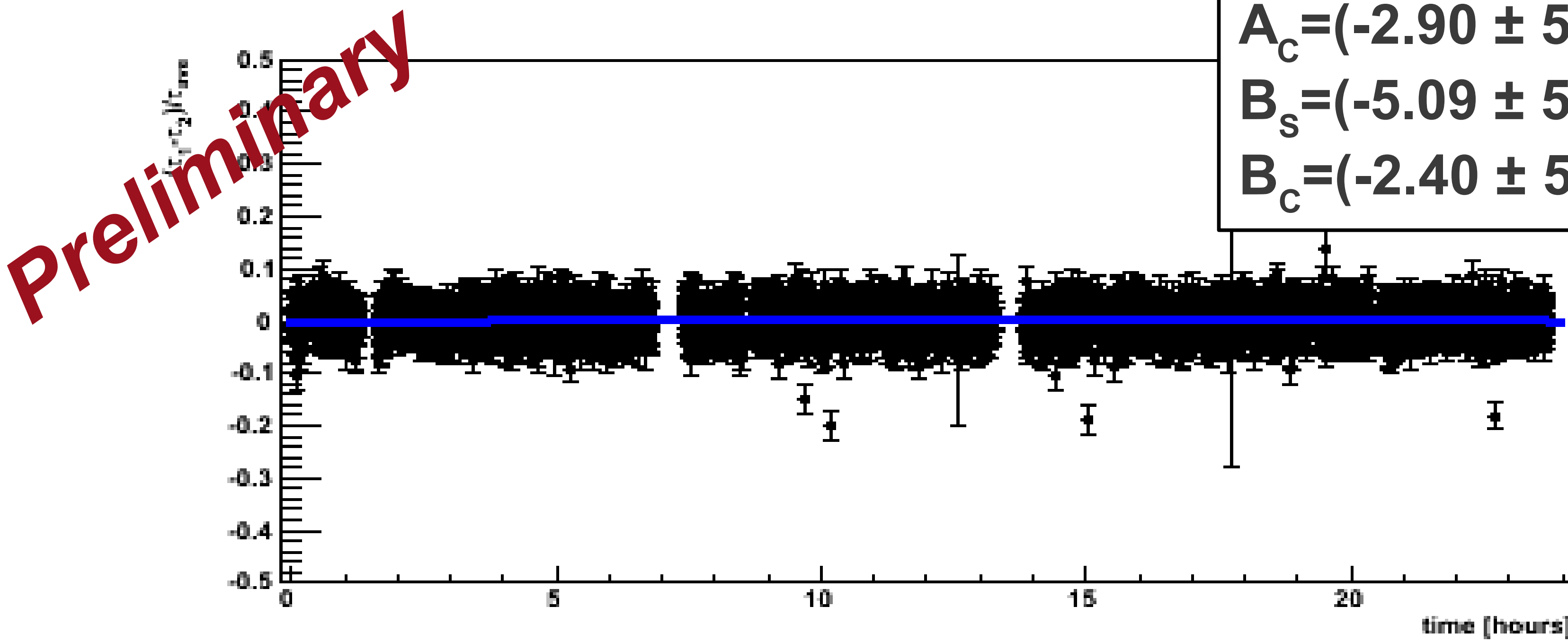
$C = (\ 4.69 \pm 3.90) \times 10^{-4}$

$A_S = (\ 0.90 \pm 5.50) \times 10^{-4}$

$A_C = (-2.90 \pm 5.55) \times 10^{-4}$

$B_S = (-5.09 \pm 5.55) \times 10^{-4}$

$B_C = (-2.40 \pm 5.56) \times 10^{-4}$



Next steps:

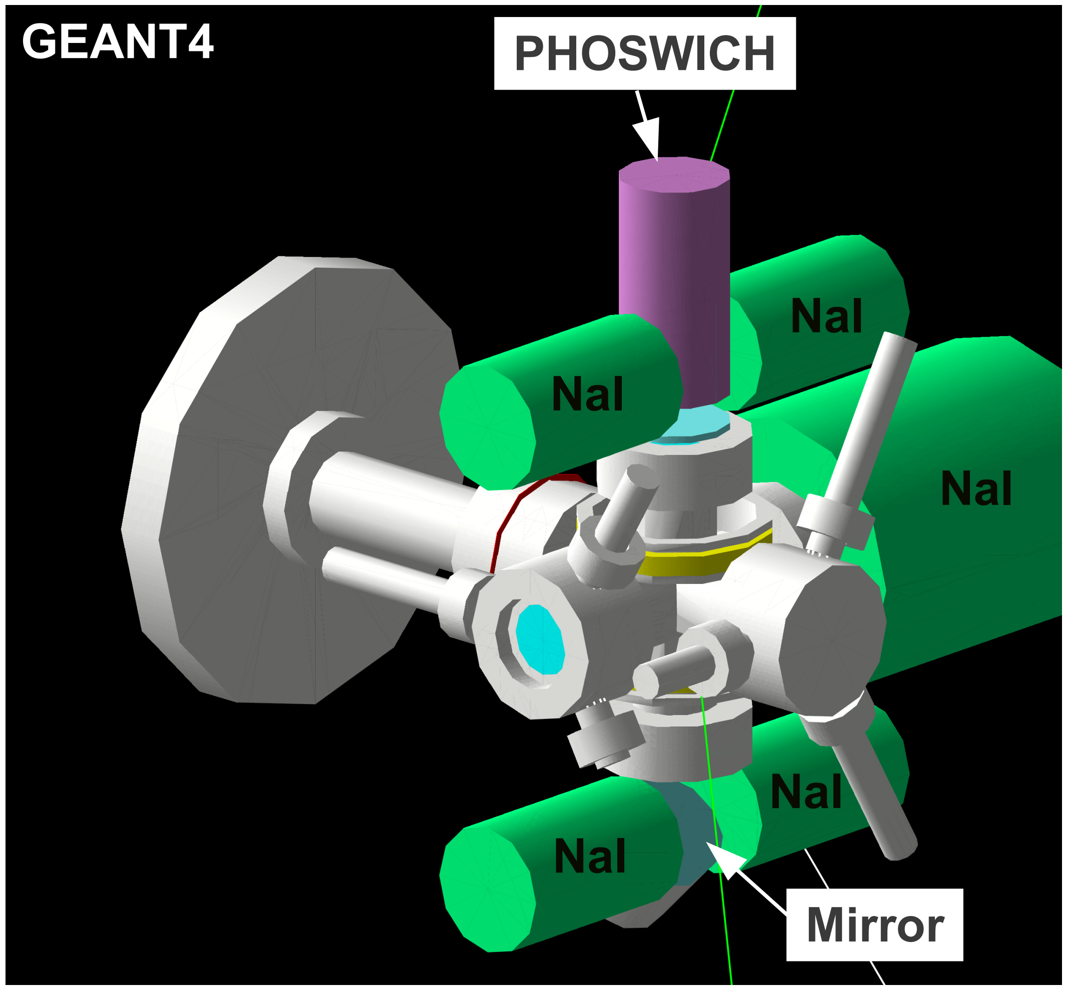
- determine polarization asymmetry

- analyze lifetimes for polarized nuclei

- evaluate and quantify systematic effects

GEANT4 simulation:

^{20}Na Atoms



Simulations needed for:

- *detector acceptances*
- *study of systematic effects (stopping position of ^{20}Na atoms, detector alignment, etc.)*

Standard Model Extension (SME):

$$\frac{d\Gamma}{dE\,d\Omega} \sim \left(1 + A_0 \frac{\langle\vec{I}\rangle}{I} \cdot \frac{\vec{p}}{E}\right) + \xi_1 \left(1 + \xi_A \left(\hat{p} \cdot \frac{\langle\vec{I}\rangle}{I}\right)\right) \hat{p}\,\hat{n} +$$

$$+ \xi_2 \frac{\langle\vec{I}\rangle}{I} \hat{n} + \xi_3\, \hat{p}_i \left(\frac{\langle\vec{I}\rangle}{I}\right)_j \rho^{ij}$$

Experiment at KVI probes ξ_2

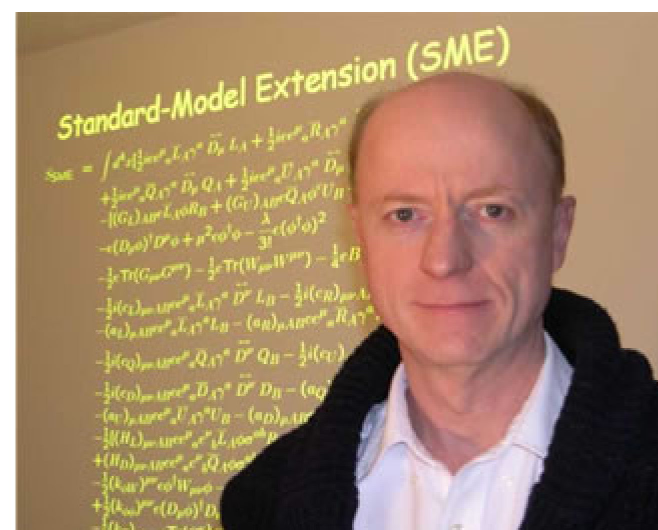
More general framework to compare with other experiments:

Standard Model Extension (SME)

D. Colladay, A. Kostelecký, PRD58 (1998) 116002)

⟶ **Talk by R. Lehnert**

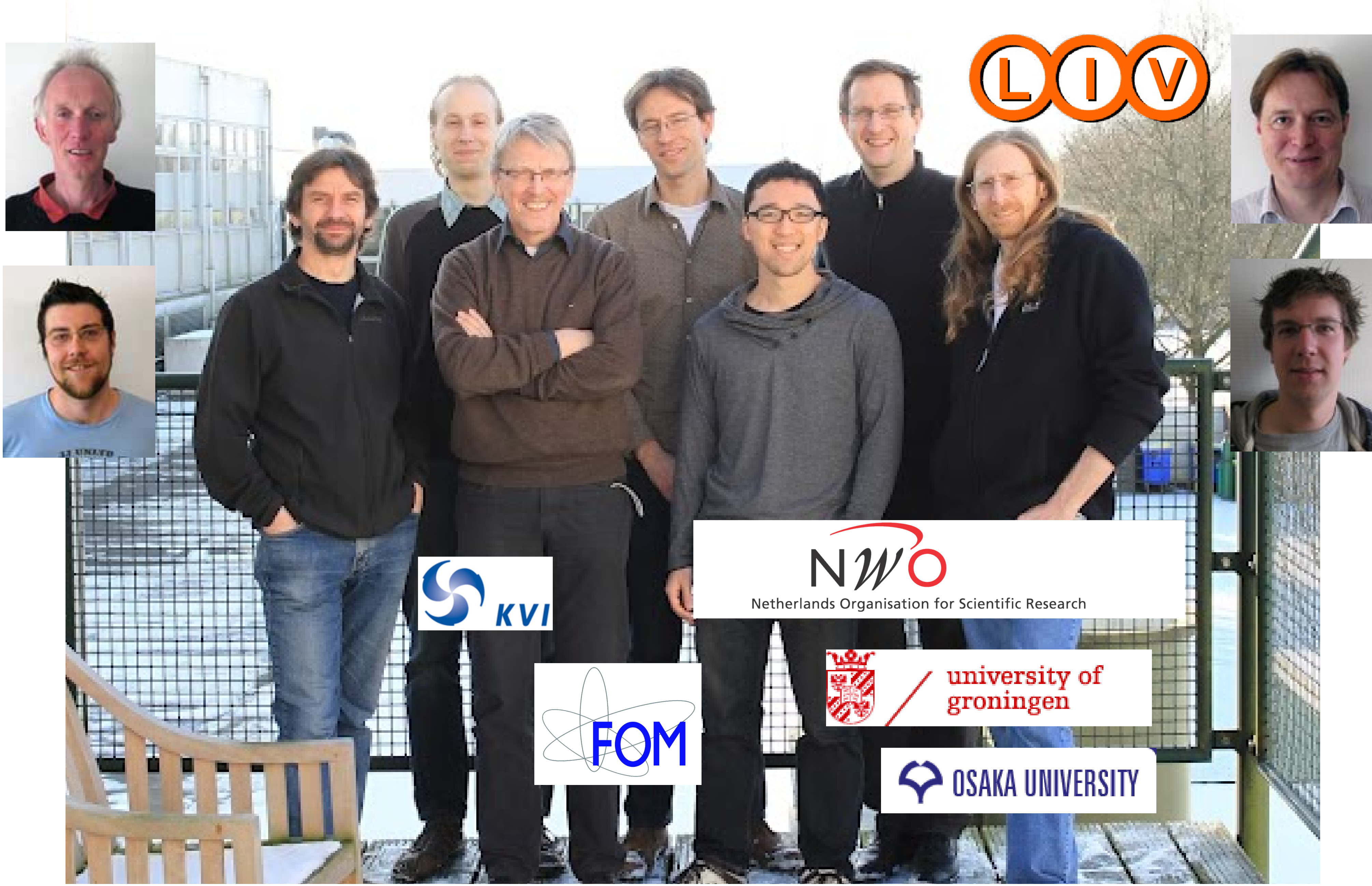
- relate ξ coefficients to SME parameters
- use galactical coordinates in sun-centered equatorial frame



Conclusions

- **Unique Test of LSB** using weak decay of polarized particles
  Probe muon, neutron, radioactive isotopes,...
- **Combined effort** from theorists and experimentalists at KVI
  Interpretation of observables in LSB framework (SME) underway
- **First dedicated experiment** studying LSB on polarized atoms
  Polarization of nuclei achieved, several 24h-periods of data on disk
- **Outlook**
  Lifetime analysis in progress, results expected soon

Thank you!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