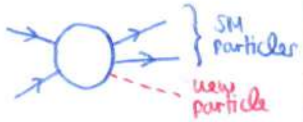
Three Frontiers of PP There are three frontiers of particle physics:

Energy Frontier

$E_{particles}$: $\mathcal{O}(\text{TeV})$

E_{probed} : $\mathcal{O}(14\ \text{TeV})$



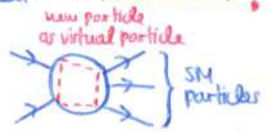
Cosmic Frontier

Intensity Frontier

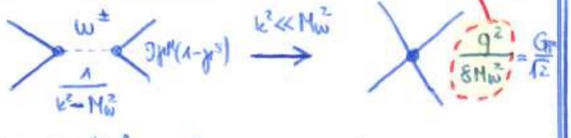
$E_{particles}$: $\mathcal{O}(\text{meV} - \text{keV})$

(accelerator PSI : 590 MeV)

E_{probed} : $\mathcal{O}(1'000\ \text{TeV})$!



Effective field approach high intensities to probe high masses or small couplings



$$\frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}}$$

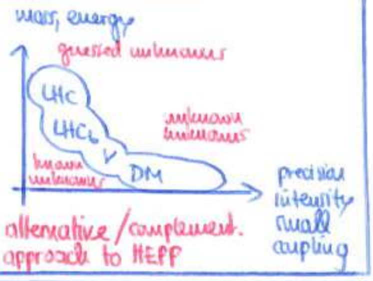
Heavy particle exchange generates new local interaction

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d\geq 5} \frac{C_n^{(d)}}{\Lambda^{d-4}} \hat{O}_n^{(d)}[\phi_{SM}] \quad \text{with} \quad \mathcal{L}_{SM} = \ldots + \underbrace{\hat{\Theta} G_{\mu\nu}\tilde{G}^{\mu\nu}}_{\text{strong CP violation}} + \ldots + \underbrace{\Lambda_{UV}^2}_{\text{hierarchy problem}} H^\dagger H + \ldots$$

why is this ~0?

→ treat SM as effective theory up to Λ

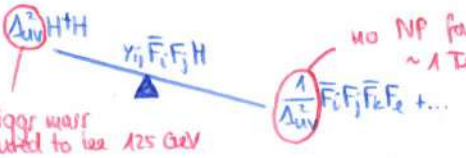
→ general and systematic approach, structure of NP need not be known! !



! → alternative/complement. approach to HEPP

Hierarchy problem

Hierarchy see-saw :



Solved by SUSY : $m_H^2 = \varepsilon \Lambda_{UV}^2 \ll \Lambda_{UV}^2$, since the contributions

cancel : $\Delta m_H = \pm \frac{\lambda_t^2}{8\pi^2}\Lambda^2$ $\bar{t}$

SM Problems

- many parameters, no explanations for values
- GUT?
- Gravity? DM? Dark Energy? Neutrino masses? matter-antimatter asymmetry? Strong CP problem? naturalness?
- origin of particle masses? Mass patterns? Hierarchy problem?
- Why three families?
- Dynamics of CP violation? C,P,T violation in weak theory - why?
- Is there LNV, BNV?

1. Low Energy Particle Physics

BSM Contributions

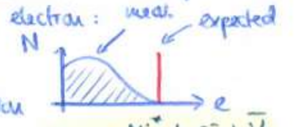
There are two classes of contributions:

- those who modify SM "allowed" processes :
  β-decays, muon g-2, Q_W, ...
- those who violate (approximate) SM symmetries :
  flavour changing neutral currents (FCNC), lepton number violation (LNV), Baryon number violation (BNV), electric dipole moments (EDM), ...

Experiments

Beta-decay $n \to p + e + \bar{\nu}_e$

discovered via energy spectrum of electron:



Wu: β-decay preferentially in direction opposite to the nuclear spin $\underset{\text{spin-5}}{Co} \to \underset{\text{spin-4}}{Ni^*} + e^- + \bar{\nu}_e$

→ violates parity : spin aligned in direction of $\vec{B}$,

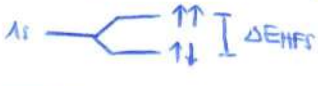
$\vec{B} \xrightarrow{P} \vec{B}$ while $\vec{v} \xrightarrow{P} -\vec{v}$ → non-isotropic

β-decay violates P symmetry

Lamb shift Retherford-Lamb experiment: measure $\Delta E(2s-2p)$ to get QED correction to prediction from Dirac equation

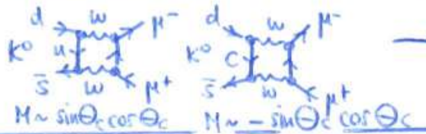
HFS $\Delta E_{HFS}^{th} = a\,\mu_p\mu_e$ predicted, did not agree with theory

$\to \Delta E_{HFS}^{th} = a(1+\varepsilon^{QED})\mu_p\mu_e$



GIM Mechanism

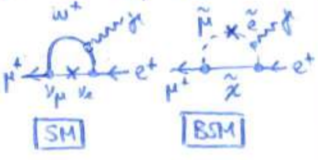
explains $Br = \frac{P(K_L \to \mu^+\mu^-)}{P(K_L \to all)} \sim 10^{-9}$



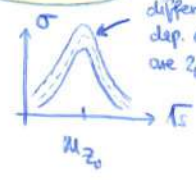
→ prediction of c quark and $m_c \sim 1.5\,\text{GeV}$ (similarly for t quark)

$\mu \to e\gamma$ $Br = \frac{P(\mu \to e\gamma)}{P(\mu \to e\bar{\nu}_e\nu_\mu)} \sim 10^{-54}$ in SM, but

$Br \sim 10^{-12}$ with BSM physics



Z_0 resonance $e^+e^- \to Z_0$



different resonance dep. on whether there are 2,3,4 families

Fundamental constants Fundamental constants are input parameters of the theory → in order to get significant predictions, the input parameters need to be known very well

$Q^{exp} = Q^{th}$ ↗ yes : limits on NP, determine fund. const. ↘ no : new physics → which kind?

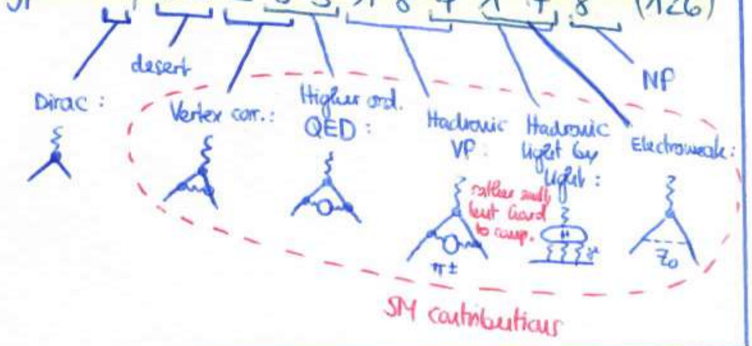
Anomalous Magnetic Moment

$H_{mag} = \vec{\mu} \cdot \vec{B}$ ⟶ Classically : $\vec{\mu} = \frac{1}{c}(\text{current} \times \text{area}) = \frac{q}{2mc}\vec{L}$

QM : $\vec{\mu} = g \cdot \frac{q\hbar}{2mc}\vec{S}$ with $|g| = 2$ (Dirac eq. with minimal substitution $p_\mu \to p_\mu + ieA_\mu \longrightarrow \frac{e}{m}\vec{S}\cdot\vec{B}$ in Hamiltonian)

Measurements : $g_p \approx 5{,}58$, $g_e \approx 2{,}002$ $\Big\}$ $a = \frac{g-2}{2} \neq 0$

$$g_\mu = 2{,}00233184178\,(126)$$



Results

Theory : $a_\mu = a_\mu(\text{QED}) + a_\mu(\text{hadronic}) + a_\mu(\text{weak})$
↳ up to 5th order!

⟶ predicted to ~350 ppb

Experiment : $a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$ or $a_\mu = \frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}\frac{\omega_a}{\tilde{\omega}_p}$

ω_a – muon precession

ω_p – NMR precession

μ_μ/μ_p – ratio of magn. moments via spectroscopy of 1s-HFS (muonium / hydrogen)

$\frac{\mu_p}{\mu_e}$ – hydrogen maser

$\frac{m_\mu}{m_e}$ – muonium HFS

$\frac{g_e}{2}$ – electron g-2

$\frac{\omega_a}{\tilde{\omega}_p}$ – this experiment

$\tilde{\omega}_p$ – av. from p⁺ NMR

⟶ always measure frequency

⟶ measured to ~540 ppb

$a_\mu^{exp} - a_\mu^{th} = (26{,}6 \pm 7{,}2) \cdot 10^{-10}$
⟶ 3,5–4σ discrepancy

} new experiment E989 at Fermilab aiming at 140 ppb
↳ at the same time: muon g-2 theory initiative

equipment moved from BNL to Fermilab

2. Muon g-2

Wiggle Plot

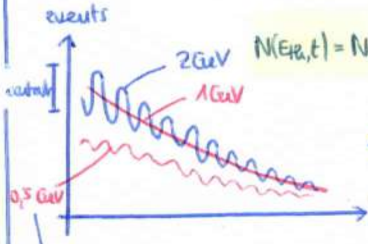
Cyclotron motion : $\vec{\omega}_c = -\frac{e\vec{B}}{m}\frac{1}{\gamma}$

Spin motion : $\vec{\omega}_s = -\frac{g e\vec{B}}{2m} - (1-\gamma)\frac{e\vec{B}}{m\gamma}$

⟶ $\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = \frac{g-2}{2}\frac{e\vec{B}}{m}$

$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{\omega_a\gamma\tau\,\bar{A}\sqrt{N}}$$

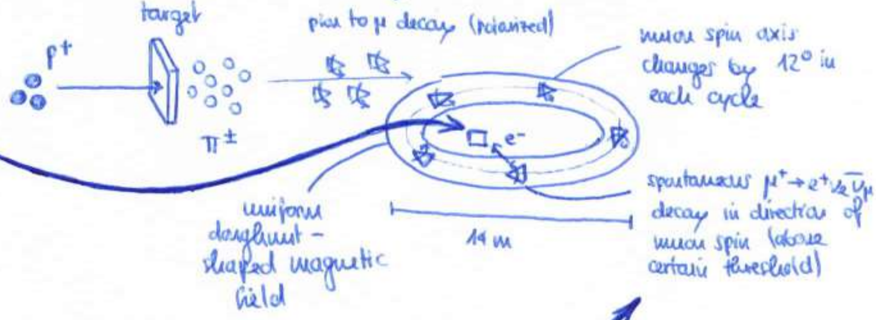
$$N(E_{th},t) = N_0(E_{th})\,\underbrace{e^{-t/\tau\gamma}}_{\text{exponential decay}}\Big[1 + \underbrace{A(E_{th})}_{\text{contrast}}\cos\big(\omega_a t + \phi_0(E_{th})\big)\Big]$$



electrons more likely to be emitted in opposite spin direction

$\omega_a = \dot{\Theta}$

Muon g-2 experiment



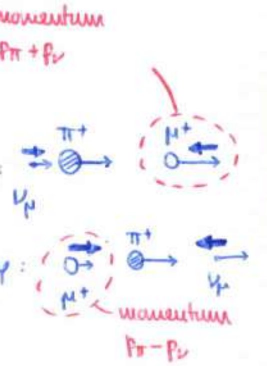
muon spin axis changes by 12° in each cycle

uniform doughnut-shaped magnetic field

spontaneous $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ decay in direction of muon spin (above certain threshold)

$\pi^+ \to \mu^+ + \nu_\mu$

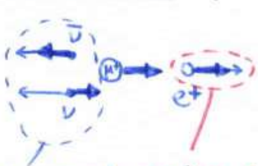
- forward decay :
- backward decay :



selected ⟶ one gets spin-polarized muons

$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$

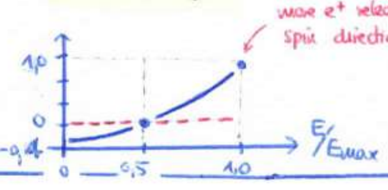
High-energy e⁺ preferentially emitted in μ⁺-spin direction



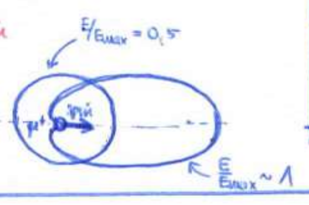
spin cancels

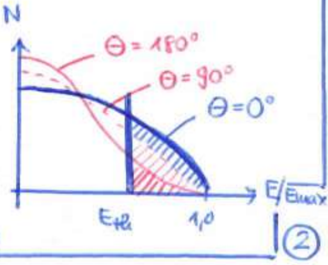
positron preferentially emitted in ↑-helicity

Asymmetry : $A_r = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$



more e⁺ released in spin direction





Experimental Principles

Beam: 24 GeV proton beam

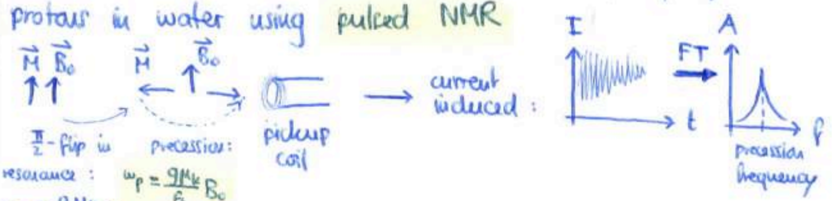
Per bunch: $10^{13} p^+ \xrightarrow{1:10^9} 10^4 \mu^+$

Magnetic field: must be very homogeneous!

1,5 T field, 14 m diameter, supercond. coils

→ E989 needs $\frac{\Delta B}{B} = 0{,}07$ ppm!

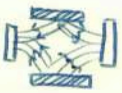
Measurement of B-field: measure precession frequency of protons in water using pulsed NMR



$\omega_{\frac{\pi}{2}} = \frac{g \mu_K}{\hbar} B_0$

$\omega_p = \frac{g \mu_K}{\hbar} B_0$

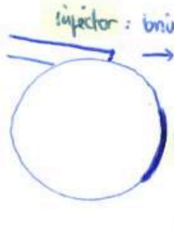
Magic momentum: Electric field is needed to confine the μ^+ axially → electric quadrupoles along ring



BMT formula: $\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2-1}\right)}_{\substack{=0 \text{ for } \gamma = 29{,}3 \\ \text{(magic momentum)}}} \vec{\beta} \times \vec{E}\right]$

electric field becomes magn. field in rest frame of μ^+

Injection:



injector: bring μ^+ into stable orbit
→ cancel 1,5 T present inside storage ring while not influencing storage ring

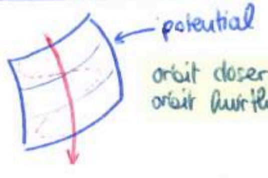
kicker: injected muons need to be kicked so that they don't hit the injector after one turn

→ 5% efficiency in filling

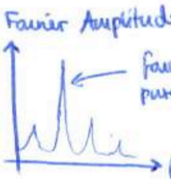
Limitations

Betatron oscillations:

$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu B - \overbrace{\left(a_\mu - \frac{1}{\gamma^2-1}\right)}^{\substack{\text{not an exact cancell.} \\ \to \text{reduced field}}} \vec{\beta} \times \vec{E} - \ldots \overbrace{(\vec{\beta} \cdot \vec{B})\vec{\beta}}^{\substack{\text{vertical oscillations} \\ \to \text{reduced field}}}\right]$$

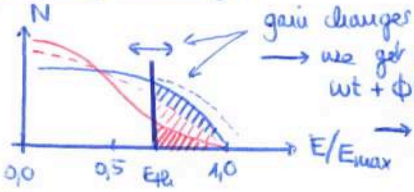


orbit closer to e^+-detectors → increased count
orbit further away → decreased count



2. Muon g-2

Detector gain change:



gain changes
→ we get a phase modulation:
$\omega t + \phi(t) = (\omega + \phi')t + \phi_0$
→ shift in frequency

Pile-up: two low-energy electrons measured instead of a high-energy one

→ segment detectors, record waveform of detector signal

Muon EDM

If the muon has an EDM (violates CP-symmetry!), the BMT-formula gets modified: $H = -\vec{d}\vec{E} - \vec{\mu}\vec{B}$ and

$\vec{\omega}_{a\eta} = \vec{\omega}_a - \eta \frac{Qe}{m}\left[\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right]$

use field in radial direction to cancel g-2 precession
$(a\vec{B} - \ldots (\vec{\beta} \times \vec{E}))$

EDM precession

Penning Traps

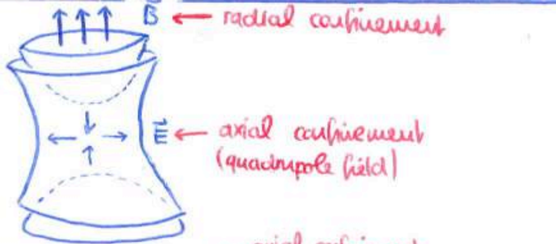
Trapping: $\vec{F} \sim -\vec{r}$ required

$\rightarrow$ $\Phi = Ax^2 + By^2 + Cz^2$ satisfies this for $A, B, C > 0$,

but $\Delta\Phi = 0 \rightarrow 2(A+B+C) = 0$ $\xrightarrow[\text{contradiction}]{}$ ↑

$\rightarrow$ confinement not possible with static electric field only

$\rightarrow$

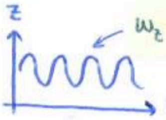


axial confinement

$$V = \frac{V_0}{d_0^2}\left(\rho^2 - \boxed{2z^2}\right)$$

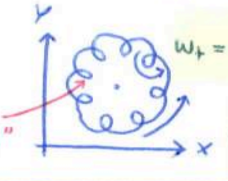
Classical Motion in Penning Traps

- Harmonic oscillation in z-direction:



$$\omega_z = \frac{qV_0}{md_0^2}$$

- cyclotron and magnetron motion in xy-direction:



"moving up the potential hill"

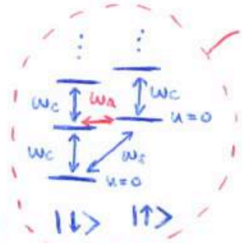
$$\omega_+ = \frac{eB}{2mc} + \sqrt{\left(\frac{eB}{2mc}\right)^2 + \frac{eV_0}{2md^2}}$$ modified cyclotron motion

$$\omega_- = \frac{eB}{2mc} - \sqrt{\left(\frac{eB}{2mc}\right)^2 + \frac{eV_0}{2md^2}}$$ magnetron motion

Geonium Atom

Electron in free space:

$$\omega_c = \frac{eB}{m}, \quad \omega_s = \frac{g}{2}\omega_c$$



✓ energy levels of quantum mechanical harmonic oscillator modes (in free space)

↳ minimal substitution in H gives $E_n = \hbar\omega_c\left(n + \frac{1}{2}\right)$

$$H = \frac{\hat{p}_x^2}{2m} + \frac{1}{2}m\omega_c^2\left(\hat{x} - \frac{\hbar k_y}{m\omega_c}\right)^2$$

relativistic corrections

$$\frac{\delta}{\omega_c} = \frac{\hbar\omega_c}{2\pi mc^2} \sim 10^{-9}$$

$\longrightarrow$

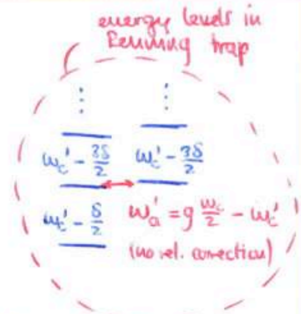
electric field:

magnetron: $\omega_m = \frac{\omega_z^2}{2\omega_c'}$

cyclotron: $\omega_c' = \omega_c - \omega_m$

anomalous: $\omega_a' = \frac{g-2}{2}\omega_c + \omega_m$

energy levels in Penning trap



experimental determination of g fairly complicated

$$\frac{g}{2} \simeq 1 + \frac{\boxed{\bar{\omega}_a} - \frac{\boxed{\bar{\omega}_z}^2}{2\bar{f}_c}}{\boxed{\bar{f}_c} + 3\delta/2 + \frac{\bar{\omega}_z^2}{2\bar{f}_c}} + \frac{\Delta\omega}{\omega}$$

$\bar{\omega}_c - 3\frac{\delta}{2}$

cavity shift

measure

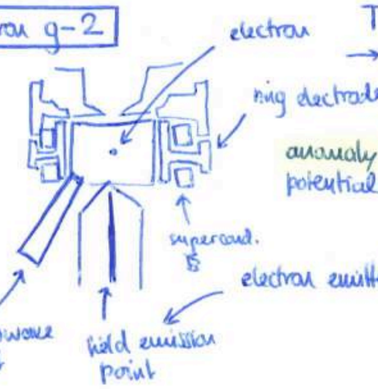
quantum jump spectroscopy

Frequencies: for $B \sim 5\,T$, $V_0 \sim 100\,V$, $d \sim 3{,}5\,mm$

$\rightarrow$ $\nu_z \sim 200$ MHz, $\nu_c \sim 150$ GHz, $\nu_s \sim 150$ GHz

$\nu_m \sim 133$ kHz

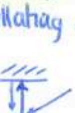
Electron g-2



$T \sim 100\,mK$ $(\hbar\omega_c/k_B \sim 7{,}5\,K)$

$\rightarrow$ only lowest cyclotron level populated

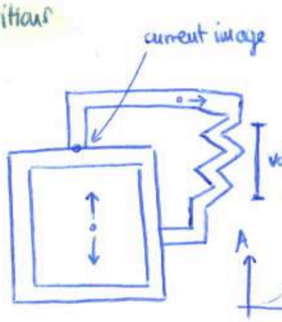
anomaly transitions driven by electrodes potentials oscillating at ω_a



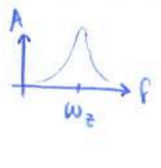
electron bounces back, gets trapped by chance

↑ cyclotron transitions

Axial motion:



$\rightarrow$ FT:

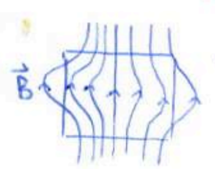


$\rightarrow$ axial motion can be measured directly

3. Electron g-2

Cyclotron frequency: Too high to be detected directly

$\rightarrow$ couple spin and cyclotron frequencies to the axial frequency: $B_z = B_0 + B_2 z^2$



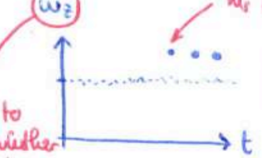
spin and cyd. level enters

$$\rightarrow H_{z0} + H_z' = \frac{1}{2}m\omega_{z0}^2 z^2 - \underbrace{\boxed{\mu_{s,c}} B_2 z^2}_{\text{modific.}}$$

$$\rightarrow \frac{\Delta\omega_z}{\omega_z} \sim 2 \cdot 10^{-8}\left(\frac{g}{2}m_s + n\right)$$

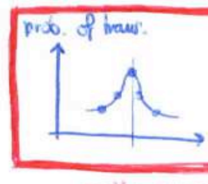
spin orient. cyclotron level

$\boxed{\omega_z}$



used to probe whether transition in n or m_s has occured

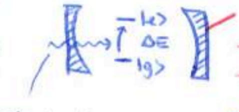
transition in n or m_s has occured



microwave frequency

Transition:

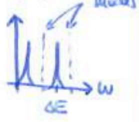
(control cyclotron damp. rate)



microwave radiation (150 GHz)

cavity suppresses decay of $|e\rangle$
$\rightarrow$ longer lifetime
$\rightarrow$ sharper peaks

$\rightarrow$ lifetime from 0,08 to 16 s



Anomalous frequency: Analogous to cyclotron frequency, use anomaly drive (179 MHz) to induce transition

Muon g-2 Theory

$$a_\mu = a_\mu^{em} + a_\mu^{had} + a_\mu^{weak}$$

$$= \sim 1 + 60\,\text{ppm} + 1{,}5\,\text{ppm}$$

$$\pm 1{,}3\,\text{ppb} \quad \pm 0{,}4\,\text{ppm} \quad \pm 0{,}02\,\text{ppm}$$

large uncertainty

→ theory limited by hadronic contributions

→ improvements in theory could lead to 8σ difference instead of only 5σ → BSM is the goal

Hadronic VP : cannot be calculated perturbatively, but must be obtained from

$$\sigma(e^+e^- \to \gamma \to \text{hadrons})$$

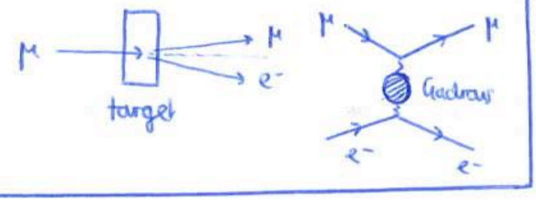
(optical theorem)

$$a_\mu^{had} \propto \int_{2m_\pi}^{\infty} ds\ \frac{K(s)}{s}\ \frac{\sigma(e^+e^- \to \text{hadr.})}{\sigma(e^+e^- \to \text{muons})}$$

(dispersion relation)

μ or e

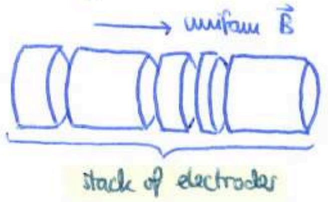
New approach to get a better handle on hadronic contributions :



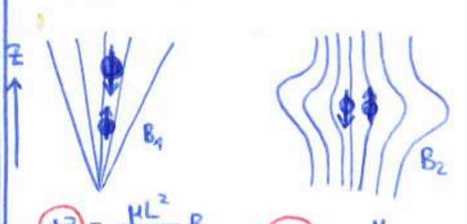
2. Muon g-2 (Advanced)

Practice : Shape

The ideal shape is difficult to manufacture → Gabrielse showed that it can be generated also with a stack of open cylindrical electrodes



Electron g-2 vs. Stern-Gerlach



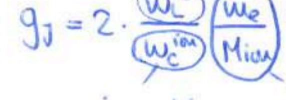
$$\boxed{\Delta z} = \frac{\mu L^2}{2\,KE} B_1 \qquad \boxed{\Delta\omega_z} = \frac{\mu}{m\omega_z} B_z$$

change in position

change in frequency

3. Penning trap (Advanced)

Bound-state g-2



$$\frac{g_{bound}}{g_{free}} \approx 1 - \frac{(Z\alpha)^2}{3} + \frac{\alpha (Z\alpha)^2}{4\pi} + \dots$$

$$g_J = 2 \cdot \frac{\omega_L^e}{\omega_c^{ion}} \frac{m_e}{M_{ion}} \frac{Q^{ion}}{e} \qquad \underline{\text{or}} \quad \frac{m_e}{M_{ion}} = \dots$$

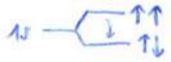
Larmor precession freq. of bound electron

ion cyclotron frequency

external input parameters

Hydrogen Played a fundamental role in the discovery of new physics:

spectroscopy, spin, nuclear force, Lamb shift, fine structure, lasers, Bose-Einstein, hydrogenic atoms, p radius



Energy levels:

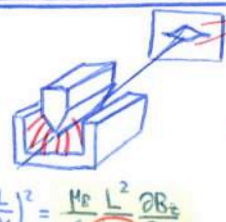
Bohr	Dirac	Lamb	HFS	proton size
n Coulomb pot.	nj Darwin spin-orbit relativity	1s-2p QED	spin proton spin	finite size of proton

Bohr: $E_n = \frac{Z\alpha^2}{n^2} m_e \rightarrow \frac{1}{\lambda} = R_\infty \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right)$

Dirac: $E_{nj} = m \left[1 - \underbrace{\frac{(Z\alpha)^2}{2n^2}}_{\text{Schrödinger}} - \underbrace{\frac{(Z\alpha)^4}{2n^4} \left[\frac{n}{j+\frac{1}{2}} - \frac{3}{4} \right]}_{\text{fine-structure}} \right]$

(Balmer doublet)
↳ different j

Stern-Gerlach:



two discrete lines
→ expected classically: a continuous spectrum

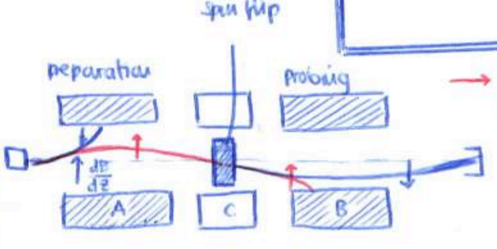
$\vec{F} = \vec{\nabla}(\vec{\mu}\cdot\vec{B})$

$z = \frac{1}{2}at^2 = \frac{1}{2}\frac{F}{m}\left(\frac{L}{v}\right)^2 = \frac{\mu_B}{4}\frac{L^2}{\boxed{KE}}\frac{\partial B_z}{\partial z}$

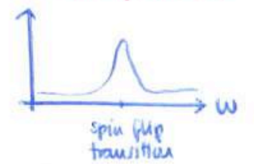
linewidth!
(the smaller the better)

→ depends on the velocities of the particles: end up at different z positions

Rabi setup



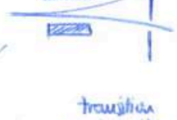
→ this setup no longer depends on velocities of the particles!

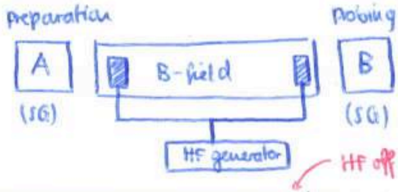


$\hbar\omega = \Delta E_{HFS} \quad (\vec{B}_0 = 0)$

$\hbar\omega = \Delta E_{Zeeman} = g\frac{e\hbar}{2m}B\Delta m \quad (\vec{B}_0 \neq 0)$

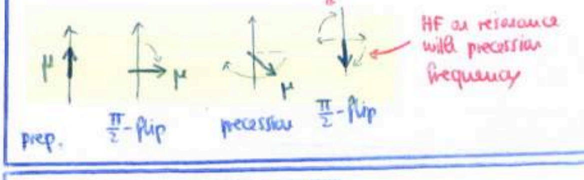
Ramsey Spectroscopy

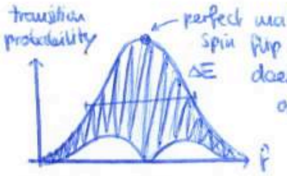




HF off resonance

HF on resonance with precession frequency

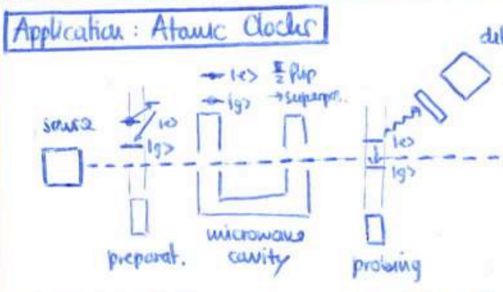




perfect match to spin flip (central peak does not depend on v)

$\frac{\Delta\omega}{\omega} \sim \frac{1}{\omega T}\sqrt{\frac{\tau_c}{t}}\sqrt{\frac{1}{N}}$

Application: Atomic Clocks



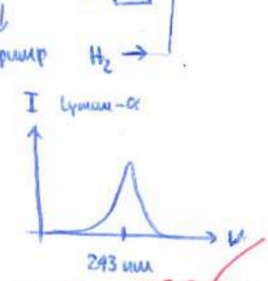
$\omega_{RF} = \frac{E_e - E_g}{\hbar} \rightarrow$ second: HFS of Cs-133 ground state

Alternative application: Qubit decoherence

1S--2S measurement Max-Planck Inst. for Quant. Opt.

Advantages: 2s is meta-stable → sharp linewidth
2-γ spectroscopy is Doppler-free

Stark effect:
E ≠ 0 → mixtures of
$2S, 2P_{\frac{1}{2}}, 2P_{\frac{3}{2}}$ → Lyman-α
decay to 1s



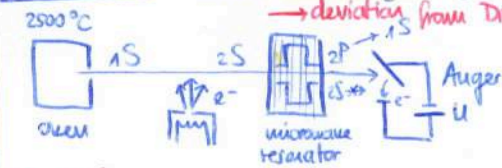
$h\nu = \frac{3}{4}R_\infty \frac{m_r}{m} + \Delta E_{rel} + \Delta E_{HFS} + \Delta E_{QED} + \Delta E_{finite\ size}$

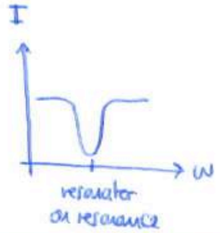
finite size of proton

4. Atomic Physics

Lamb Shift Measure $\Delta E(2P_{\frac{1}{2}} - 2S_{\frac{1}{2}}) \sim 2\,\mu eV$ ← Dirac theory predicts 0

→ deviation from Dirac theory





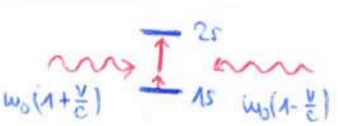
1s stable
2s meta-stable: $2S \rightarrow 1S + \gamma + \gamma$
2P short lifetime: $2P \rightarrow 1S + \gamma$

Doppler-free Spectroscopy

Doppler shift

$\delta_D = 7\cdot10^{-7}\omega_0\sqrt{\frac{T}{M}}$

Two-photon spectroscopy:



→ total frequency: $2\omega_0$ → Doppler free!

reduce T
drop laser beam → wait long → small velocities
→ sharp, symmetric lineshape

Systematics:
- second order Doppler shift
- Stark/Zeeman shifts in excit. region
- AC stark shift → minimize laser I
- black-body radiation

$\frac{\delta\nu^{exp}}{\nu^{exp}} \sim 4\cdot10^{-15}$ → determ. R_∞, r_p or $\Delta E(1S-2S)$

Laser frequency

$\nu_L = \underbrace{n\Delta\nu}_{\text{known}} + \underbrace{\Delta\bar{\nu}}_{\text{beating freq.}}$

(we know the freq. more or less) $\nu_L - \nu_c$

CP symmetry CP violation needed to explain matter-antimatter asymmetry

$H = -\vec{\mu}\vec{B} - \vec{d}\vec{E}$ and $E \xrightarrow{CP} \vec{E}$, $\vec{B} \xrightarrow{CP} -\vec{B}$, $\vec{d} \xrightarrow{CP} -\vec{d}$, $\vec{\mu} \xrightarrow{CP} -\vec{\mu}$

$\rightarrow H \xrightarrow{CP} -\vec{\mu}\vec{B} + \vec{d}\vec{E}$ → EDM violates CP symmetry

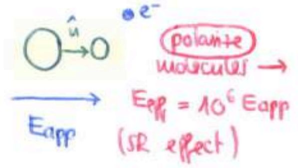
same transformation properties as spin $\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{S}$
$\vec{d} = \eta\left(\frac{q}{2m}\right)\vec{S}$

eEDM with Molecules

$d_e \sim 10^{-27}\, e\cdot cm$

$\rightarrow \vec{d}_e\vec{E} \ll \vec{\mu}_e\vec{B}$

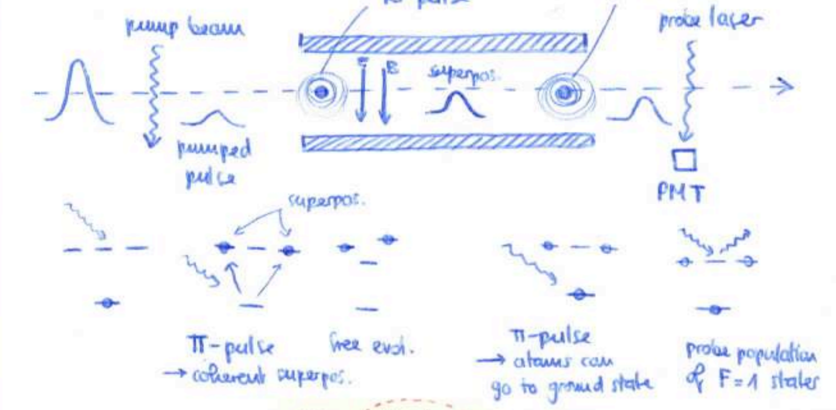
$\rightarrow -\vec{d}_e\vec{E} \longrightarrow -\vec{d}_e\vec{E}_{eff}$



polarize molecules → $E_{eff} = 10^6 E_{app}$ (SR effect)

eEDM Setup

Ramsey setup:



Π-pulse → coherent superpos.

free evol.

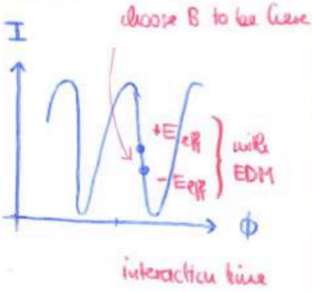
Π-pulse → atoms can go to ground state

probe population of F=1 states

flip electric field

$\pm 2 d_e \eta E_{eff} \frac{t}{\hbar}$

$2\mu_B B \frac{t}{\hbar}$



interaction time

$|0,0\rangle$ $\frac{1}{\sqrt{2}}(|1,1\rangle + |1,-1\rangle)$ $\frac{1}{\sqrt{2}}\left(|1,1\rangle e^{-i(\phi_{d_e}+\phi_B)} + |1,-1\rangle e^{i(\phi_{d_e}+\phi_B)}\right)$ $|0,0\rangle \underbrace{\cos(\phi_{d_e}+\phi_B)}_{\text{probe}} + \frac{1}{\sqrt{2}} \underbrace{\sin(\phi_{d_e}+\phi_B)}_{\text{probe}} \left[-|1,-1\rangle + |1,1\rangle\right]$ $\rightarrow I = \cos^2\left[\frac{2}{\hbar}(\mu_B B \pm \eta d_e E_{eff})t\right]$

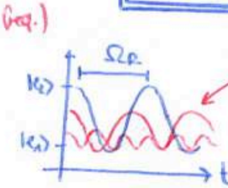
→ ACME : $|d_e| < 8{,}7 \cdot 10^{-29}\, ecm$

Two-level system

Two-level system with classical radiation

5. EDM

$H(t) = H_0 + \underbrace{\overset{\hbar\Omega_R \text{ (Rabbi freq.)}}{q\vec{r}\hat{u}E_0}\cos(\omega t + \phi)}_{\text{perturbation}}$



detuning → smaller amplitude, larger frequency

→ time dep. perturbation theory:

$|\psi(t)\rangle = e^{i\cdots}\left[\cos\left(\frac{\Omega}{2}t\right) + i\frac{\Delta/\hbar}{\Omega}\sin\left(\frac{\Omega}{2}t\right)\right]|e_1\rangle + ie^{i\cdots}\left[\frac{\Omega_R}{\Omega}\sin\left(\frac{\Omega}{2}t\right)\right]|e_2\rangle$

$\Delta = \varepsilon_2 - (\varepsilon_1 + \hbar\omega)$, $\Omega = \sqrt{\Omega_R^2 + (\Delta/\hbar)^2}$
↑ detuning

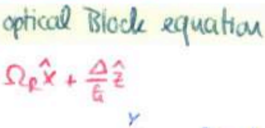
Density operator: $\rho = |1\rangle\langle 1| + |2\rangle\langle 2| + |1\rangle\langle 2| + |2\rangle\langle 1|$ $V_z = \rho_{22} - \rho_{11}$

→ $\frac{d\vec{V}(t)}{dt} = \vec{\Omega} \times \vec{V}(t)$ optical Bloch equation

Bloch vector related to matrix el. of ρ

$\vec{\Omega} = -\Omega_R\hat{x} + \frac{\Delta}{\hbar}\hat{z}$

Zero detuning:



Period: $\frac{2\pi}{|\Omega|}$

$|\psi(t)\rangle = e^{i\cdots}\cos\left(\frac{\Omega}{2}t\right)|e_1\rangle + ie^{i\cdots}\sin\left(\frac{\Omega}{2}t\right)|e_2\rangle$

Non-zero detuning: axis of rotation is changed

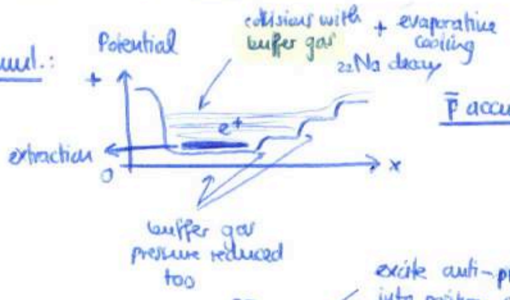
CPT Symmetry Still assumed to hold: CPT symmetry valid within all local, unitary, Lorentz-invariant field theories in flat space.

→ Measure HFS. in hydrogen/antihydrogen: is it the same?
↳ CPT predicts that H and $\bar{H}$ must have similar properties

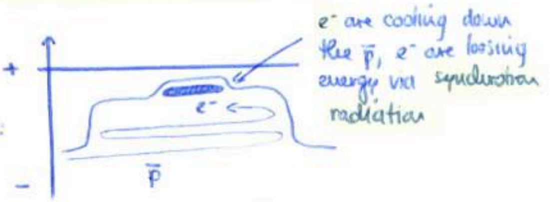
Anti-Hydrogen Trapping $\bar{p} + e^+ \rightarrow \bar{H}^*$ not allowed (does not conserve energy + momentum)

$\bar{p} + e^+ + e^+ \rightarrow \bar{H}^* + e^+$, $\bar{p} + e^+ \rightarrow \bar{H}^* + \gamma$ or $\bar{p} + Ps^* \rightarrow \bar{H}^* + e^-$ possible

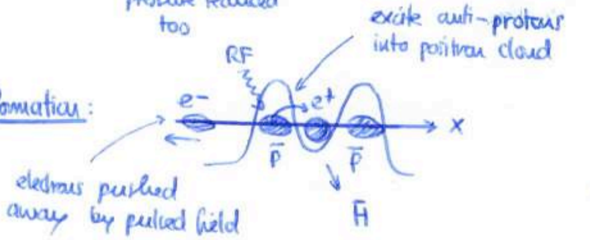
Positron accumul.:



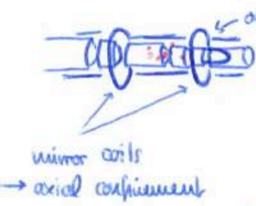
$\bar{p}$ accum.:

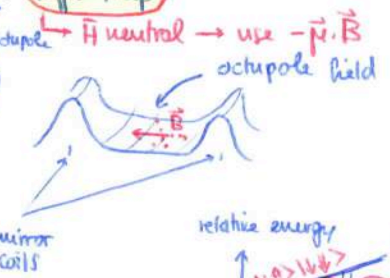


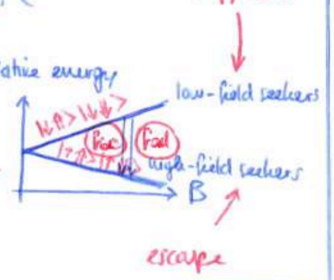
Anti-Hydr. formation:



Anti-Hydr. trapping: Ioffe-trap
↳ $\bar{H}$ neutral → use $-\vec{\mu}\cdot\vec{B}$





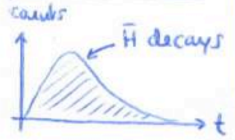


Anti-Hydrogen Detection

Ramp down magnetic field → $\bar{H}$ not trapped anymore → hit the walls: $e^+ + e^- \rightarrow 2\gamma$
$p + \bar{p} \rightarrow n\pi$ (4,5 on average)

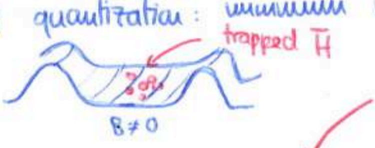
→ reconstruct π, γ tracks, identify coincidences between the two

6. Anti-Hydrogen Experiments



HFS in Anti-Hydrogen

To have a defined quantization: minimum non-zero in octupole field



extrapolate $\omega_{HFS}(B=0)$ from f_{ad}, f_{bc}

induce transitions from "low-field seekers" → "high-field seekers"
→ $\bar{H}$ escape the trap, hit the wall → measure π, γ

$\frac{\Delta f}{f} = 2 \cdot 10^{-12}$ → most precise anti-matter measurement!

7. Lepton Flavour Violation

Lepton and quark family structure

(neutrino oscillations)

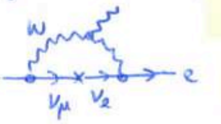
no generational transition to first order

mass eigenstates are not equal to flavor eigenstates:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \end{pmatrix}}_{\text{CKM matrix}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$\mu \to e\gamma$ not observed, $Br = \frac{P(\mu \to e\gamma)}{P(\mu \to e \nu_\mu \bar{\nu}_e)} < 4 \cdot 10^{-13}$ meas.

SM:



$Br \sim 10^{-54}$

↑ new physics would significantly enlarge this

complicated physics could go on in intermediate states

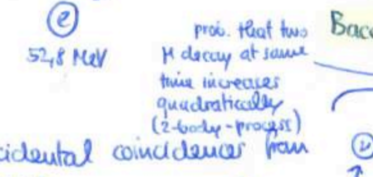
(effective field theory)

(exchange particles)

↑ new physics in virtual loops

MEG (Mu et Gamma) Experiment

Decay topology:

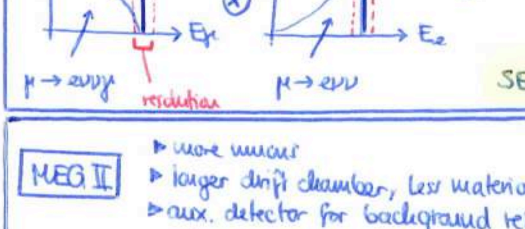


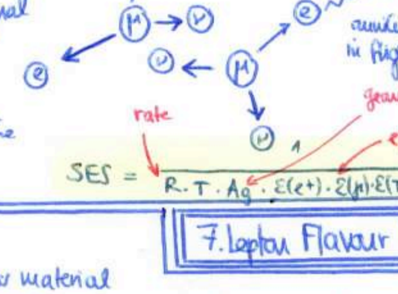
good resolution needed:

$$B_{acc} \approx \underbrace{R_\mu^2}_{} \underbrace{\Delta E_e}_{\text{flat}} \underbrace{\Delta E_\gamma^2}_{\text{slope}} \Delta \Theta^2 \Delta t$$

prob. that two μ decay at same time increases quadratically (2-body-process)

Background: accidental coincidences from three-body decays





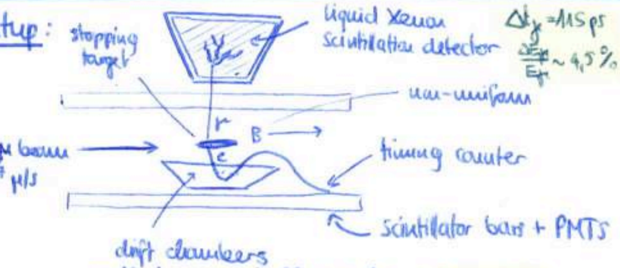
$$SES = \frac{1}{R \cdot T \cdot A_g \cdot \varepsilon(e^+) \cdot \varepsilon(\gamma) \cdot \varepsilon(TRG)\varepsilon(sel)}$$

rate

geom. acc.

efficiency

Setup:



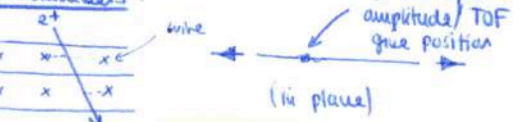
$\Delta t_\gamma = 115$ ps

$\frac{\Delta E_\gamma}{E_\gamma} \sim 4,5\%$

→ 16 chambers in 10° intervals → p_{e^+}; vertex

- thin: low material budget
- fast: intensity frontier → high rate
- stable: precision measurement → backgr. rejection

Drift chambers:



(transverse)

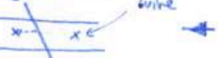
read out signal left and right → amplitude/TOF give position

$\frac{\Delta p_{e^+}}{p_{e^+}} \sim 1\%$ $\Delta\Theta_{e^+} \sim 10$ mrad

Tiles detector:

$\Delta t = 100$ps

COBRA magnet: produces B-field gradient → B field is compensated outside so that it does not disturb the PMTS



might miss electrodes with a B-field

Advantage of gradient B-field:

few rotations then out penetration depth does not dep. on angle

Analysis: variables: $E_\gamma, E_e, t_{e\gamma}, \Phi_{e\gamma}, \Theta_{e\gamma}$

signal box covered (blind analysis), analysis performed on data outside the box (background)

Results: $B(\mu^+ \to e^+\gamma) < 4,2 \cdot 10^{-13}$

MEG II

- more muons
- longer drift chamber, less material
- aux. detector for background rej.
  - ↳ measure second positron
- LXe calorimeter with more volume
- pixelized timing counters
  - → less pile-up, improved resol.

improvements on MEG are ongoing

Mu3e

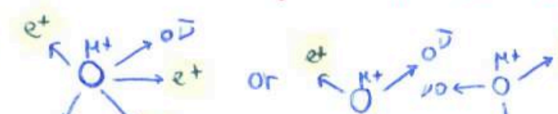
energy-mom. cons.
temporal coincid.
spatial coincid.

SM: $Br \sim 10^{-50}$

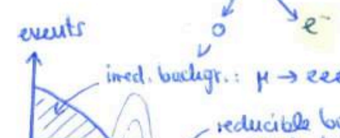
$Br < 10^{-16}$ measured

→ ~10^{17} muons needed (high intensity)
→ background supp. ~10^{-16} (high precision)

Background:



atomic electron (Bhabha scatt.)



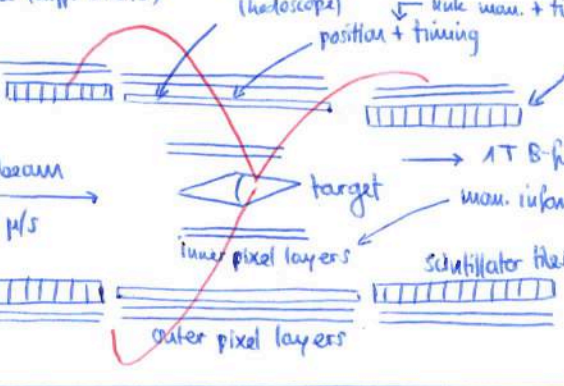
irred. backgr.: $\mu \to eee\nu\nu$

reducible backgr.: accidental coincid.

signal (diff. units)

→ vertex resolution, timing resolution, kinematix recostr.

Setup:



Target: hollow double-cone

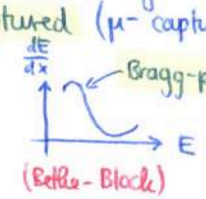
→ distribute e^-, e^+ in space
→ e^-, e^+ released close to surface

Mu3e Challenges: tracking of 10^9 e/s with sub-MeV momentum resolution in a multiple scatter. dom. regime

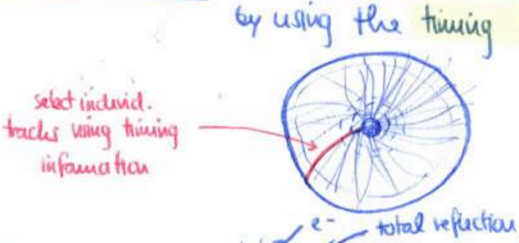
Tracker: 300 MPx, 20 million pictures per second, thinner than a hair
custom-made → driving the technological development!

Beam: μ^+ are easier to get than μ^- : p^+ smashed on target → abundance of positive charges
μ^+ not captured (μ^- captured to form muonic hydrogen)

low-energy muons are easy to stop

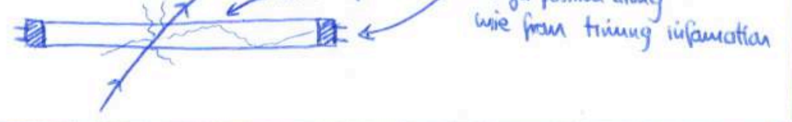


Track-Reconstruction: Si tracker read out with 20 MHz → hundreds of electron tracks in one frame → sort them by using the timing information from the Hodoscope + scintillating tiles
→ 100ps resolution

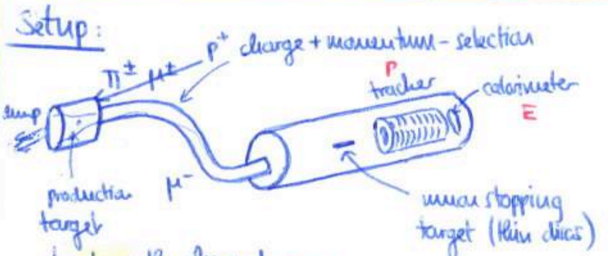


design and construction ongoing

Fibres:



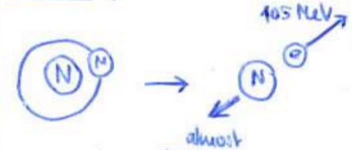
Setup:

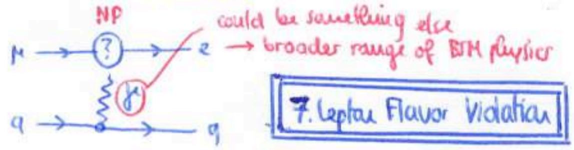


↳ traps the charged particles and accelerates them towards the transport solenoid

10^{10} μ/s

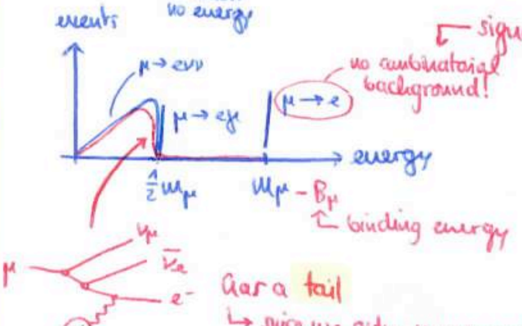
Mu2e μ → e conversion on nucleus (Fermilab)





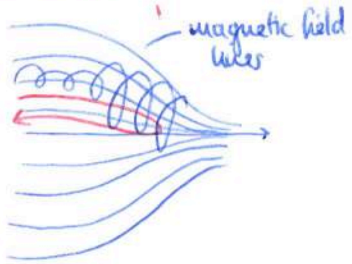
7. Lepton Flavor Violation

↳ signal at higher E than almost all BG



has a tail
↳ since we only measure one particle, we have limited possibilities to reject background

Magn. Bottle:



$\frac{p_\perp^2}{B}$ = const. → at some point $p_\perp = p$
→ no parallel momentum → reflection

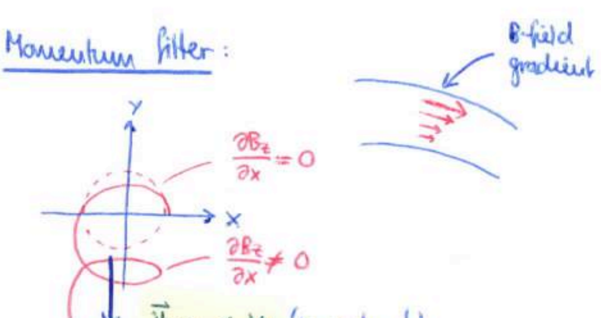
Conversion Principle: stop muons in Al
↓
muons quickly move to 1s orbit
(a_0 ~ 20 fm, nuclear radius ~ 4 fm)
↓
decays
$\mu \rightarrow e\bar{\nu}_e\nu_\mu$ ~ 40%
$\mu + Al \rightarrow X + \nu_\mu$ (capture) ~ 60%
$\mu + Al \rightarrow e^- + Al$

rel. small since Al is light

signal

Sensitivity: $2 \cdot 10^{-17}$

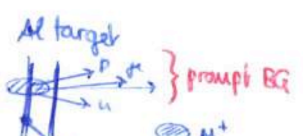
Momentum filter:



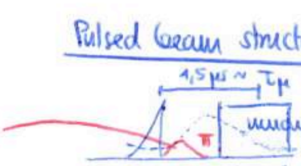
$\vec{v}_{Drift} \propto v_\perp$ (momentum!)

Tracker:

we only want to detect large circles (E = 105 MeV)



Pulsed beam structure:



$pN \rightarrow \pi^- X$
$\pi^- N \rightarrow \gamma N'$
$\gamma N \rightarrow e^- e^+ N$

Wait until all the muons generated in the production target has passed

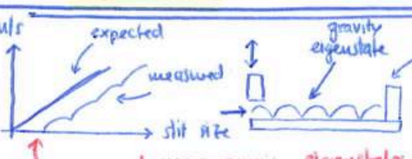
Neutron Properties $m_n = 939,57$ MeV $(m_n > m_p)$ $S^P = \frac{1}{2}^+$ $d_n < 3\cdot 10^{-26}$ ecm $V = \frac{3956 \text{ m/s}}{\lambda_{dB}[A°]}$

$\rightarrow n \rightarrow p + e^- + \bar{\nu}_e$ possible $g = -3,83$ $q = (-0,4 \pm 1,1)\cdot 10^{-21} e$

$\tau = 880$ s

Interactions

▶ Gravity : $\frac{\Delta V_{grav}}{\Delta h} \approx \frac{\boxed{102,5 \text{ neV}}}{m}$ energy scale of neutron exp.



more and more gravity eigenstates can pass through

$\vec{\mu}_n = \gamma_n \hbar \vec{S}$ with $\gamma_n = \frac{e}{2m_n} g_n$

▶ Magnetic : $\frac{\Delta V_{mag}}{\Delta B} = \pm 60,3 \frac{\text{neV}}{\text{T}}$

→ use to select one spin state :

$Q = 782$ keV

▶ Weak : $n \xrightarrow{Z} p + e^- + \bar{\nu}_e$ there are weak nucleon-neutron interactions (P-viol.)

→ test g_A, g_V of nucleon

▶ Strong : $U_0 \sim 40$ MeV ↱ depth of potential

$R_0 \sim 1\text{-}2$ fm ↳ range of potential

$\sigma \propto \frac{|\langle f|H|i\rangle|^2}{\phi} \propto \frac{1}{V_n}$ const. in energy range of thermal neutrons

History Rutherford: postulated neutron 1920 ← bound $e^- + p^+$

Bothe-Becker : $\alpha + {}^9\text{Be} \rightarrow {}^{12}\text{C} + X$ ← neutral

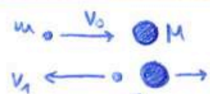
Curie : X have sufficient energy to eject p's from paraffin

$\rightarrow X \neq \gamma$

Chadwick : replaced paraffin with other targets

$\longrightarrow M_n = 0,9 M_p \pm 10\%$

→ neutron!



unknown mass

→ obtained from kinematics

Bainbridge : mass of p, d using spectrograph

Chadwick : $\hbar\omega + d \rightarrow p + n$

$\rightarrow M_n = 1,0080 \pm 0,0005$

$\rightarrow M_n > M_p + M_e$

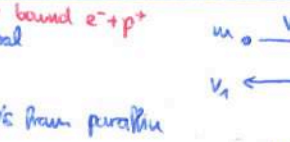
↳ n cannot be $p^+ + e^-$

Neutron production

▶ Laboratory : (α,n) - sources $\sim 10^{-4}\, n/\alpha$ ← α-particle hits light atom

(γ,n) - sources $\sim 10^{-6}\, n/\gamma$

^{252}Cf spont. fission $\sim 10^{9}\, n/s$



▶ Reactor : induced fission of ^{235}U

▶ Spallation : protons on solid target (Pb)

→ "evaporation" of neutrons from the excited nucleus

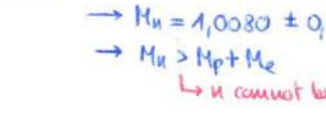
3. Neutron production, properties and applications

Fission :

only 0,7%

→ enrichment

Spallation :



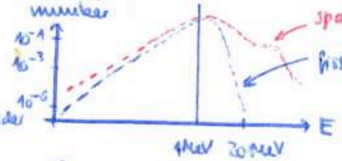
limited by heat and radiation damage of target

Moderation : deceleration by repeated elastic scattering of n with nuclei

↳ e.g. H_2O

Neutron reactor (FRM II) :

don't point directly towards fuel elements to avoid detecting γ



We want neutrons with ~1-100 eV for nuclear reaction and < 1 eV for material studies

→ moderation!

Thermal : 25 meV

Cold : 5 meV

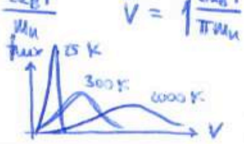
Ultracold : < 250 neV

Maxwell distribution :

$$N(v)dv = N_0 \left(\frac{m_n}{2\pi k_B T}\right)^{\frac{3}{2}} e^{-\frac{m_n v^2}{2k_B T}} dv$$

moderator temperature

$V_{max} = \sqrt{\frac{2k_B T}{m_n}}$ $\bar{V} = \sqrt{\frac{8k_B T}{\pi m_n}}$



Refraction index :

$n = \frac{V_{med}}{V_{vac}} \approx 1 - \frac{\lambda^2}{2\pi} \rho b$

neutron ↓ nucl. dens. ↓ ↑ scattering length

critical angle

$\vartheta_c \approx \lambda \sqrt{\frac{\rho b}{\pi}}$

total reflect. for $\vartheta < \vartheta_c$

AC, move charges up (voltage multiplication)

PSI : SINQ : Cockcroft - Walton : 800 keV

Small ring cyclotron : 72 MeV

Large Ring Cyclotron : 590 MeV

$\omega_c = \frac{qB}{m\gamma}$ $\left(\frac{m v^2}{r} = qBv\right)$

accelerate protons

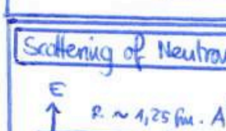
↳ source : hydrogen gas

→ ionized by electric field

(Pb)

→ spallation target (SINQ)

Scattering of Neutrons off Nuclei



potential of nuclei

$\psi(r) = e^{i\vec{k}\vec{r}} + \underbrace{f(\Theta)}_{-a} \frac{e^{ikr}}{r}$

scattering length

form factor (strong interact.)

TISE : $-\frac{\hbar^2}{2m'} \nabla^2 \psi(\vec{r}) + V(\vec{r}) = E\psi(\vec{r}) \rightarrow (\vec{\nabla}^2 + \vec{k}^2)\psi(\vec{r}) = \frac{2m'}{\hbar^2} V(\vec{r})\psi(\vec{r})$

reduced mass ↖ $\frac{\hbar \vec{k}^2}{2m'}$

$\rightarrow$ Green's function $\psi(\vec{r}_1) = e^{i\vec{k}\vec{r}_1} - \frac{2m'}{\hbar^2}\int d\vec{r}_2^{\,3}\, V(\vec{r}_2)\psi(\vec{r}_2) \frac{e^{ik|\vec{r}_1 - \vec{r}_2|}}{4\pi|\vec{r}_1 - \vec{r}_2|}$

→ Dyson series + Born approx. : $\psi(\vec{r}_1) = e^{i\vec{k}_0\vec{r}_1} - \underbrace{\frac{2m'}{\hbar^2}\int d\vec{r}_2^{\,3}\, V(\vec{r}_2) \frac{e^{ik|\vec{r}_1 - \vec{r}_2|}}{4\pi|\vec{r}_1 - \vec{r}_2|} e^{i\vec{k}_0\cdot\vec{r}_2}}$

reduces to $-a$ for $|r_1| \gg R$

$\longrightarrow \boxed{V(r_2) = \frac{2\pi\hbar^2}{m'} a\,\delta(\vec{r}_2)}$

Fermi pseudo potential

Wave function inside square well potential :

$u(r) = A\sin(kr)$ with $K = \sqrt{\frac{2m(E - U_0)}{\hbar^2}}$

$f(\Theta) \rightarrow -a$, since no angular depend. is expected : $L = mvd \rightarrow d \sim \frac{\hbar}{mv} = \lambda \gg R$

Neutron incident on matter sees "forest" of delta functions" : $\boxed{U(r) = \frac{2\pi\hbar^2}{m}\sum_i b_i\,\delta(\vec{r} - \vec{r}_i)} = \frac{2\pi\hbar^2}{m} \underbrace{b N(r)}$

full mass ↑ bound scattering length ↗ nuclear density

refractive index

$\rightarrow \boxed{n_r} = \sqrt{1 - \frac{U}{E}} = \boxed{\sqrt{1 - \frac{4\pi b N}{k^2}}}$

Motivation

- **Cosmology**: neutron decay influences the dynamics of primordial (Big Bang) nucleosynthesis

$\sim 1s \begin{cases} n + e^+ \leftrightarrow p + \bar{\nu}_e \\ n + \nu_e \leftrightarrow p + e^- \end{cases}$

$\sim 2s \; \{ n \rightarrow p + e^- + \bar{\nu}_e$

$\sim 3\text{min} \; \{$ nucleosynthesis

- **Test of unitarity of CKM-matrix**
  → non-unitarity sign of NP

$$\underbrace{\frac{1}{\tau_n} \propto G_F^2 (g_V^2 + 3g_A^2) |V_{ud}|^2}$$ with $\lambda = \frac{g_A}{g_V}$

vector coupling (g_V), axialvector coupling (g_A), CKM matrix ($|V_{ud}|$)

$$\rightarrow \tau_n = \frac{(4908{,}7 \pm 1{,}9)s}{|V_{ud}|^2 (1 + 3\lambda^2)} \rightarrow \boxed{|V_{ud}|^2} + |V_{us}|^2 + |V_{ub}|^2 = 1 \, ?$$

neutron

so far: yes!

$\rightarrow \Delta\tau/\tau, \; \Delta\lambda/\lambda < 3 \cdot 10^{-4}$ needed

- **Search for BSM physics**

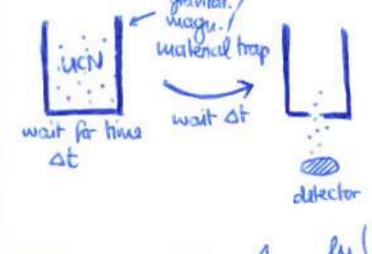
Lifetime puzzle: different values measured, trends (885 s → 880 s; blinded analysis!)
different values for different methods (>4σ)
↳ bottle vs. beam

9. Neutron Lifetime

Storage (Bottle) Experiments

$$\frac{1}{\tau} = \frac{1}{\tau_n} + \frac{1}{\tau_{abs}} + \frac{1}{\tau_{up}} + \frac{1}{\tau_{loss}}$$

τ_{abs}: neutrons absorbed by nuclei
τ_{up}: up-scattering with gas molecules



best result: $\tau_n = 877{,}7 \pm 0{,}7 + 0{,}4/0{,}2\,s$

Neutrons needed: $\frac{1}{\tau} = + \frac{\ln\left(\frac{N_1}{N_2}\right)}{t_2 - t_1} \rightarrow \delta\left(\frac{1}{\tau}\right) = \sqrt{\left(\frac{1}{N_1 \Delta t}\right)^2 \underbrace{\delta N_1^2}_{N_1} + \left(\frac{1}{N_2 \Delta t}\right)^2 \underbrace{\delta N_2^2}_{N_2}}$

$$= \frac{1}{\Delta t} \sqrt{\frac{1}{N_1} + \frac{1}{N_2}}$$

→ for 10^{-4}: 1000 fillings à 10'000 UCN

Poisson distribution: $\underbrace{p(k)} = \lambda^k e^{-\lambda} \frac{1}{k!}$

probability of given number of events occuring in fix time

$\mu = \lambda$
$\sigma^2 = \lambda$

UCN in Maxwellian spectrum: $S_{UCN} \propto N_0 \left(\frac{V_{F,c}}{k_B T}\right)^{\frac{3}{2}}$

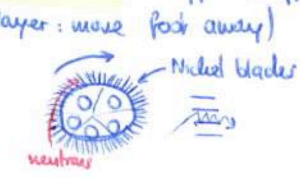
Fermi pot. ($V_{F,c}$), moderator temp. (T)

ILL: $\phi_0 = 10^{15}\,n\,cm^{-2}s^{-1} \rightarrow S_{UCN} \approx 100\,cm^{-3}$

→ why not moderator at 0,5 K?
→ elastic scattering on one nucleus stops for λ too large

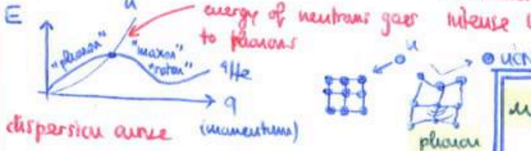
UCN production:

- **UCN turbine**: Doppler shift (like soccer player: move foot away)



- **"Down-scattering"**: inelastic scattering on superfluid He or solid deuterium

PSI uses solid deuterium → most intense UCN source



dispersion curve

→ no absorption of UCN in He
→ storage time limited only by wall collisions and up-scattering on phonons

$S_{UCN} \sim 2500\,cm^{-3}$

monochromator made from multiple graphite crystals reflects neutrons with a wavelength of 0,89 nm by 60° out of the main beam
→ Helium converter

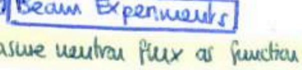
Storage Experiments - Overview:

- material bottle:
  problem of energy-dep. losses
- magnetic storage:
  storage ring, magneto-gravitational traps, Ioffe traps
- magnetic UCN traps

future experiments: stability of experiment, control of losses, measurem. of decays, control of energy spectrum important
→ TUM, ILL, Los Alamos

Beam Experiments

measure neutron flux as function of TOF



$$\phi_0 \exp(-10ms/1000s) \approx \underbrace{(1 - 10^{-5})\phi_0}_{\text{small relative change}}$$

→ better: measure neutron decay products! $\frac{dN}{dt} = -\frac{N}{\tau_n} = \frac{\overset{\text{flux}}{\downarrow}\!\!\!\!\!\! SV}{\tau_n}$

Ultracold Neutrons: storage properties are material dependent:

- strong: reflection off "forest of delta functions" for low energies
- gravity: 102 neV/m
- magnetic: ~60 neV/T

→ UCN can be trapped in material (magnetic) traps
└ E_{kin} < 250 neV, v < 7 m/s, λ > 600 Å, T < 2 mK

UCN Loss Mechanisms:
- losses due to non-ideal traps (gaps / slits)
- inelastic scattering on walls

- absorption on walls
- magnetic traps: spin flip

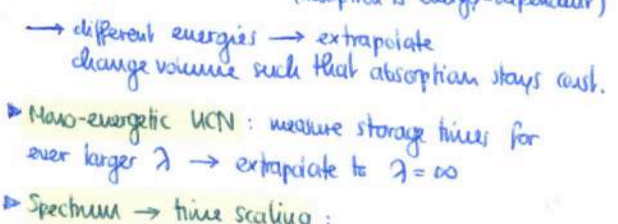
$|R|^2 = 1 - \mu(E, \Theta)$ — average over Θ

→ losses highly energy dependent!

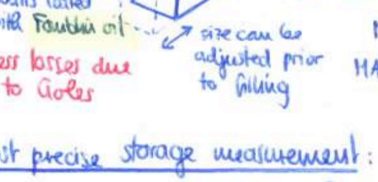
Problems of UCN gas: energy-dependent losses! (absorption is energy-dependent)

→ different energies → extrapolate
change volume such that absorption stays const.

- Mono-energetic UCN: measure storage times for ever larger λ → extrapolate to λ = ∞
- Spectrum → time scaling:



MAMBO:

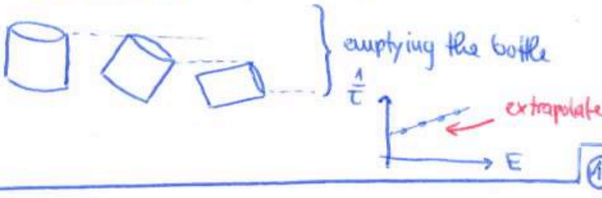


→ less losses due to holes

MAMBO I: (887,6 ± 3)s
MAMBO II: (880,7 ± 1,2)s

Most precise storage measurement:

Measurement as a function of E:



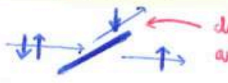
10. Properties of the neutron spin and magnetic interactions

Polarized Neutrons

$P = 2\langle S_z \rangle$ ← ensemble average

B-field → two possible spin orientations: $P = \frac{N_+ - N_-}{N_+ + N_-}$ (spin up: N_+, spin down: N_-)

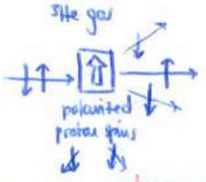
Production: ▸ spin-dependent reflection:



different critical angles for each spin

▸ spin-dependent absorption:

▸ spin-dependent scattering:



Efficiency: $P = \frac{T_+ - T_-}{T_+ + T_-}$ ← polarization $\quad T = \frac{T_+ + T_-}{2}$ ← transmission

→ usually $\underbrace{P\sqrt{T}}_{\text{quality factor}}$ is optimized, since $\sigma_{exp} \approx \frac{1}{P\sqrt{N}} \sim \frac{1}{P\sqrt{N_{init} \cdot T}}$

Guiding Neutron spin

Adiabatic spin rotation: if B-field changes sufficiently slow, spin will change with it

Larmor spin precession: $\frac{d\vec{\mu}}{dt} = \vec{\mu} \times \gamma \vec{B}$ (γ: gyromagnetic ratio) $\quad \gamma = \frac{e}{2m} \cdot g$

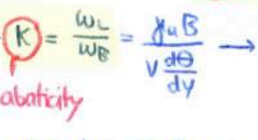
Larmor precession with ω_L

Adiabatic spin flip: $\omega_B = v \cdot \frac{d\theta}{dy}$ (v: speed of neutron)

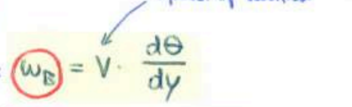
$\rightarrow K = \frac{\omega_L}{\omega_B} = \frac{\gamma_n B}{v \frac{d\theta}{dy}} \rightarrow$ we need $K > 10$ for an adiabatic rotation without loss

K: adiabaticity

Non-adiabatic spin flip: polarization will not reorient, but simply precess around new field direction while keeping its initial direction
→ one can effectively flip the beam polarization w.r.t. the guide field

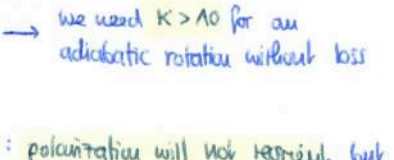


Rotating Frame:
Adiab. Spin Manipulation:



$\vec{B}_{eff} = \vec{B}(t) + \vec{\Omega}/\gamma$

$\frac{d\vec{\mu}}{dt} = \vec{\mu} \times (\gamma \vec{B}(t) + \vec{\Omega})$



→ $B_{eff} \parallel x'$ for $\Omega_{rf} = \gamma B_0$
→ spin flipped

$$\left.\begin{aligned} \frac{\pi}{2} &\overset{!}{=} -\gamma_n B_1 \tau \\ \pi &\overset{!}{=} -\gamma_n B_1 \tau \end{aligned}\right\} \text{for } \Omega_{rf} = -\gamma_n B_0 = \omega_L$$

³He Spin Filter

For ³He: $\sigma_\pm = \sigma_a (1 \mp P_N)$ ← average cross-section 5000 barns

→ one polarization fully absorbed, the other fully transmitted

$P = \tanh(O P_{He})$ $\quad T = -\exp O \cosh(O P_{He})$ (O: opacity)

³He polarization: ▸ Spin-exchange optical pumping (SEOP): polarize by spin-exch. with optically pumped Rb vapour

▸ optical pumping (MEOP): polarize with high power lasers at low pressures

spin relaxation due to magnetic-field gradients and wall collisions
→ ³He Gas to be repolarized regularly!

Neutron mirror polarizer

$n = \frac{k_{med}}{k_{vac}} = \sqrt{1 - \frac{V}{E}} \approx 1 - \frac{V}{2E}$ with $V = \frac{2\pi\hbar^2}{m_n} Nb \pm \mu B$ ($\pm\mu B$: only relevant for UCN)

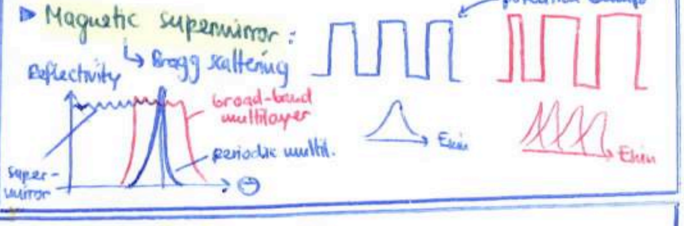
$\rightarrow \theta_c = \lambda \sqrt{\frac{Nb}{\pi} \pm \mu B \frac{m_n}{2\pi^2 \hbar^2}}$
→ different critical angles depending on spin

mirrors bought off-shelf

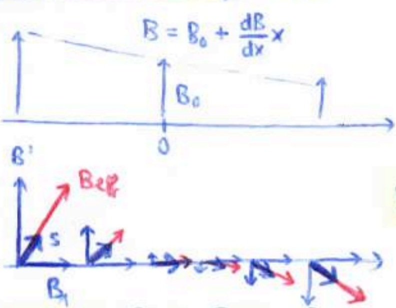
▸ Magnetized Fe foil: magnetized with permanent magnets
▸ Polarizing bi-layer mirror: non-magnetic/magnetic bilayer

$R_\pm \propto [N_a b_a - N_b (b_b \pm p)]^2 \rightarrow$ arrange s.t. $R_- = 0$

▸ Magnetic supermirror:
↳ Bragg scattering



Adiabatic Fast Passage Flipper:



$B_{eff} = \sqrt{B'^2 + B_1^2}$

$B_1(t) = B_1 \cos(\Omega_{rf} t)$, Ω_{rf} ← $\gamma_n B_0$

$B' = B_0 + \frac{dB}{dx} x - \frac{\Omega_{rf}}{\gamma_n} = \frac{dB}{dx} x$

→ no dependence on particle velocity!
↳ as long as we satisfy K < 10

11. nEDM

Motivation

- CP violation → $\underbrace{\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \cdot 10^{-10}}_{\text{baryogenesis}}$ →
  - B no. violation
  - C, CP violation — needed for baryogenesis (Sakharov criteria)
  - thermal non-equilibrium
- constraints on BSM physics
  → e.g. SUSY

these experim. predict a non-zero EDM

EDM violates CP: $H = -2(\mu\vec{\sigma}\vec{B} + d\vec{\sigma}\cdot\vec{E}) \xrightarrow{T,\,CP} -2(\vec{\mu}\vec{\sigma}\vec{B} - \underbrace{d\vec{\sigma}\vec{E}}_{\text{behaves like spin}})$ → violates CP

baryogenesis at electroweak scale

→ nEDM has killed more theories than any other single experiment: GUT SUSY, electroweak baryogenesis, …

The value of nEDM

$$d_n = \underbrace{10^{-16}\,e\cdot\text{cm}}_{\frac{e}{v}\frac{\alpha}{4\pi}}\,(\Theta + \delta_n^{BSM}) + \underbrace{d_n^{CKM}}_{\text{weak interaction contrib. } \sim 10^{-32}\,e\cdot\text{cm}} \underbrace{< 1{,}8 \cdot 10^{-26}\,e\cdot\text{cm}}_{\text{new PSI value}}$$

small contribution: no pure weak 1-loop contribution, gluonic 2-loop contribution

strongly suppressed → 3 loops

Θ: strong CP violation: $\Theta \sim 10^{-10}$

→ why? → Peccei-Quinn theory

↳ strong CP problem

(complex phase in CKM matrix)

$$\delta_n^{BSM} = \left(\frac{v}{\Lambda}\right)^2 \cdot \sin\phi_{CP} \cdot y_F\, F$$

Λ: BSM mass scale → $M \gtrsim 5\,\text{TeV}$

→ nEDM useful in measuring Θ, Λ

→ limits on CP violating physics

Experimental Techniques

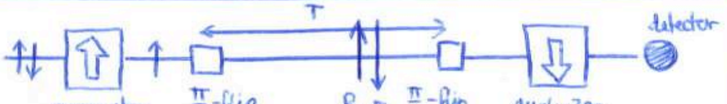
$V_{mag} = -\mu_N\vec{\sigma}\vec{B} \rightarrow \Delta E_{mag} = \hbar\omega_L = 2\mu_n B$

$V_{edm} = -d_n\vec{\sigma}\vec{E} \rightarrow \Delta E_{edm} = \hbar\omega_{EDM} = 2d_n E$

$$d_n = \hbar\,\frac{f_{n,\uparrow\downarrow} - f_{n,\uparrow\uparrow}}{4E}$$

→ flip E-field to get EDM contribution

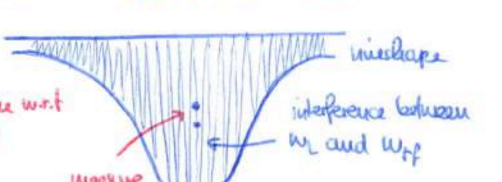
Ramsey method:



$$N_\downarrow = \frac{\langle N\rangle}{2}\left[1 + \alpha\cos\left(\underbrace{(\omega_{rf} - \omega_L)T}\right)\right]$$

$\frac{4d_nE}{\hbar}T$

derive w.r.t ω



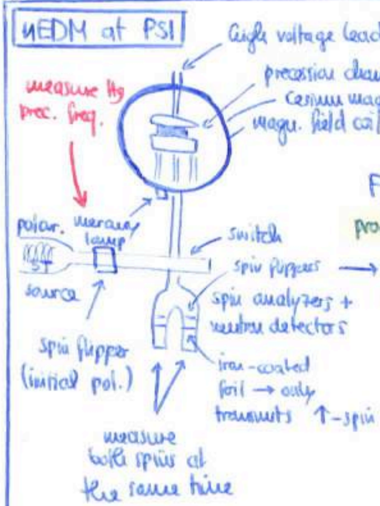
$$\sigma = \frac{\hbar}{2\alpha \boxed{T} E\sqrt{N}}$$

stat. uncertainty

α: visibility of resonance

sensitivity increases with T → use stored UCN instead of beam

nEDM at PSI



free precession for 180 s

Filling UCN: optimize product $\propto\sqrt{N}$ → ~20 s

spin flippers → neutrons are getting lost in wall collisions + dephasing!

Beam setup: dominant systematic effect: $B_v = -\frac{\vec{v}\times\vec{E}}{c^2}$

($\vec{E}$-field produces $\vec{B}$-field in rest frame of neutrons) → longer TOF

→ systematics reduced

→ $\sigma(d_n) \sim 10^{-24}\,e\cdot\text{cm}$

Stored UCN: can be trapped (seen before), storage properties are material dependent!

$$\sigma = \frac{\hbar}{ET\alpha\underbrace{e^{-\frac{T}{T_2}}}_{\text{decoherence time}}\sqrt{2N_0\underbrace{(e^{-T/\tau_s} + e^{-T/\tau_f})}_{\text{losses at walls}}}}$$

→ 200 s is the best possible storage time

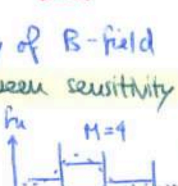
→ many cycles: $\underbrace{\sigma = \frac{\hbar}{2\alpha TE\sqrt{NM}}}_{\text{only for Gaussian noise}}$

(M cycles)

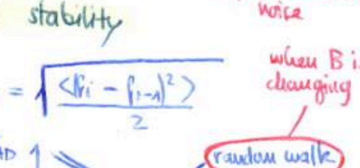
problem: stability of B-field

→ trade-off between sensitivity and stability

Allan deviation:



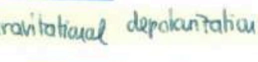
$$\sigma_{AD} = \sqrt{\frac{\langle(f_i - f_{i-1})^2\rangle}{2}}$$



when B is changing

Depolarization:

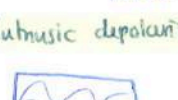
- Gravitational depolarization:



fast: $B_0 + \langle z\rangle_f \cdot g_z$

slow $B_0 + \langle z\rangle_s \cdot g_z$

- intrinsic depolarization:

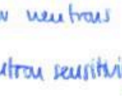


same decoherence for fast/slow neutrons

B-field stability: should be better than neutron sensitivity per cycle → $\delta B \leq 100\,\text{fT}$

→ on the order of the magnetic field in the brain

→ magnetic shield (coil cage)



Mercury comagnetometer: extract B field from Larmor frequency for Hg atoms → correct UCN frequency:

$$R = \frac{\omega_n}{\omega_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}\Big(1 \underbrace{\mp \frac{\partial B}{\partial z}\frac{\Delta h}{|B_0|} + \frac{\langle B_\perp^2\rangle}{|B_0|^2} \mp \delta_{Earth} + \dots}_{\text{systematic effects} \rightarrow \text{vary!}}\Big)$$

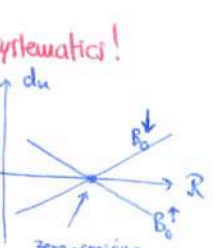
different for different $\hat{B}_0$ → vary systematics!

center of mass offset

different behavior between n (adiabatic) and Hg (non-adiabatic)

rotation of Earth

E-field → B-field in rest frame



Motivation Neutron decay data useful:
- ▸ determine couplings: G_F, V_{ud}, $\lambda = \frac{g_A}{g_V}$ ← neutron!
- ▸ unitarity of first row of CKM matrix

Needed to understand solar cycle: $p + p \to d + \nu_e + e^+ \propto \lambda^2$

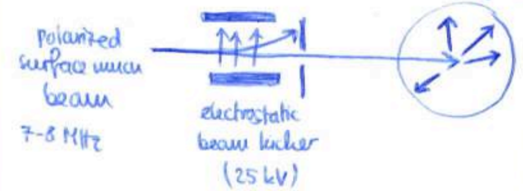
$$\boxed{\frac{1}{\tau_n} \propto \boxed{G_F^2}\left(g_V^2 + 3g_A^2\right)|V_{ud}|^2} \quad \text{and} \quad \lambda = \left|\frac{g_A}{g_V}\right| e^{i\Phi_{VA}}$$

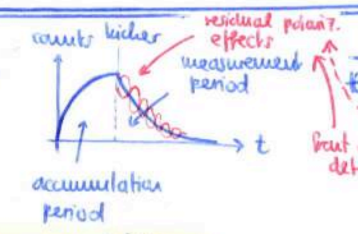
G_F^2: measured with muons (very precise)

Φ_{VA} ← CP, T, ... violation

→ τ_n, V_{ud}, λ depend on each others → test of SM

MuLAN experiment (μ lifetime)





$$N(t) = N_0 e^{-t/\tau} + B$$

Systematics: time-dependent systematics are the core concern:
- ▸ instrumental issues
  - PMT gains
  - pileup ← detector cannot resolve two particles
  - kicker voltage sag
- ▸ physics issues
  - spin polarization
  - non-flat backgr. sources

→ precisest lifetime ever measured!
$\tau = 2{,}196980(2)\ \mu s \to G_F = 1{,}1663787(6) \cdot 10^{-5}\ \mathrm{GeV}^{-2}$

Weak parity violation

$^{60}\mathrm{Co} \longrightarrow {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$

→ e^- preferentially emitted in direction of Co-spin

$$dW \propto 1 + \underbrace{A}_{\text{asymmetry}}\vec{P}\,\frac{\vec{p}_e}{E_e}$$

$$\boxed{\frac{N^1 - N^2}{N^1 + N^2} = kA\beta}$$

measure asymmetry!

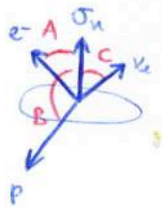
→ develop a theory of weak interaction

12. Weak interaction, muon decay and neutron beta decay correlations

Neutron decay correlation experiments

$$n \longrightarrow p + e^- + \nu_e \qquad Q = m_n - m_p - m_e - m_\nu = 782{,}3\ \mathrm{keV}$$

p: 750 eV, e^-: 781,6 keV, ν_e: 782,0 keV



$$W \propto \xi\left(1 + \underbrace{a}_{\lambda}\frac{\vec{p}_e\vec{p}_\nu}{E_eE_\nu} + b\frac{m_e}{E_e} + \frac{\vec{\sigma}_n}{\sigma_n}\cdot\left(\underbrace{A}_{\lambda}\frac{\vec{p}_e}{E_e} + \overset{\lambda}{B}\frac{\vec{p}_\nu}{E_\nu} + \underbrace{D}_{\text{sensitive to }\Phi_{VA}}\frac{\vec{p}_e \times \vec{p}_\nu}{E_eE_\nu}\right) + \ldots\right)$$

→ measure A, B, a, ... → overdetermined problem → test SM

PERKEO II: measure A, B, C

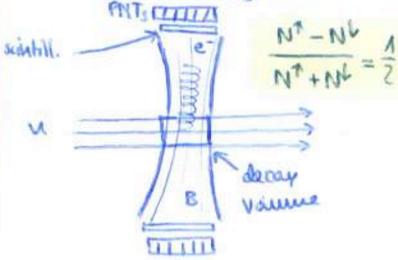
Calibration with known decays for energy DAQ

crossed analyzer:

Get rid of fast particle via Bragg scattering

λ small → d too large
→ no Bragg peak

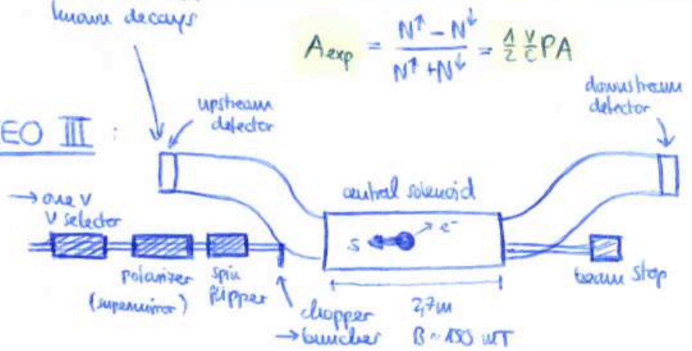
} wavelength cutter



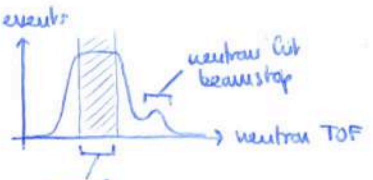
$$\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} = \frac{1}{2}AFP\frac{p_e}{E_e}$$

PERKEO III:

$$A_{exp} = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} = \frac{1}{2}\frac{v}{c}PA$$



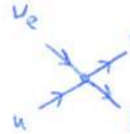
→ 50'000 decays/s in continuous beam mode
200 decays/s in pulsed mode



Theory: Fermis Golden rule: $\frac{dw}{dE} = \frac{2\pi}{\hbar}|T_{fi}|^2 \underbrace{\frac{d\rho(E)}{dE}}_{\text{phase space}}$

$$T_{fi} = -i(2\pi)^4\delta^{(4)}\left(\textstyle\sum p_i\right)\mathcal{M}$$

$$\mathcal{M} = \underbrace{G_V}_{\text{effective theory}}\underbrace{\left(\bar{u}_p\gamma^\mu u_n\right)}_{\text{Vector}}\underbrace{\left(\bar{u}_e\gamma_\mu u_\nu\right)}_{\text{Vector}}$$



→ one could also use $\underbrace{\bar{u}u}_{+}, \underbrace{\bar{u}\gamma^5 u}_{-}, \underbrace{\bar{u}\gamma^5\gamma^\mu u}_{+}, \underbrace{\bar{u}\sigma^{\mu\nu}u}_{+/-}$

→ combine different signs to get parity violation

$$\boxed{\gamma^\mu \to \gamma^\mu(1 - \gamma^5)} \quad \text{or} \quad \gamma^\mu\underbrace{\left(G_V - G_A\gamma^5\right)}_{\lambda = \left|\frac{g_V}{g_A}\right|e^{i}\ \text{for nucleon states}}$$

$$\text{CKM:}\quad \underbrace{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}}_{\text{weak eigenstates}} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\text{CKM}}\underbrace{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}_{\text{mass eigenstates}}$$

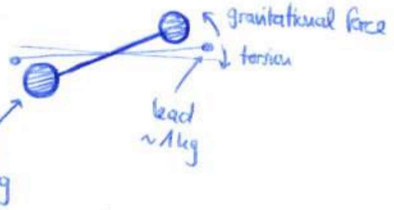
13. Gravitationally bound states with neutrons

Gravitational force

Equivalence principle: $m_i = m_g \rightarrow a = \frac{m_g \cdot g}{m_i} = g$ → all bodies fall at same rate

Newton: $F_G = G \frac{m_1 m_2}{r^2} \longrightarrow g = G \frac{M_E}{R_E^2} = 9{,}81 \frac{m}{s^2}$

G: $6{,}67 \cdot 10^{-11} \frac{m^3}{kg\,s}$ → Cavendish torsion balance:



Einstein: Gravity is a curvature of spacetime

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Gravitational Refractometer

$$\underbrace{m_n}_{\text{mass of neutron}} \cdot g \cdot h = \underbrace{2\pi\hbar^2 \rho \frac{b_c}{m_n}}_{\text{Fermi potential}}$$

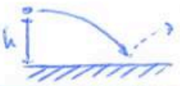
→ determine b_c (scattering length) precisely!

Mass of the neutron

$$n + p \longrightarrow d + \gamma$$

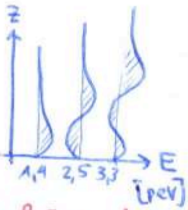
$$\rightarrow m_n = \underbrace{(m_d - m_p)}_{\substack{\text{measure cyclotron freq.}\\ \text{in ions traps}\\ \text{(Penning traps)}}} + \boxed{\frac{E_\gamma}{c^2}}$$

gamma ray spectrometer → measure wavelength via Bragg scattering



UCN - Gravitational Quantum States

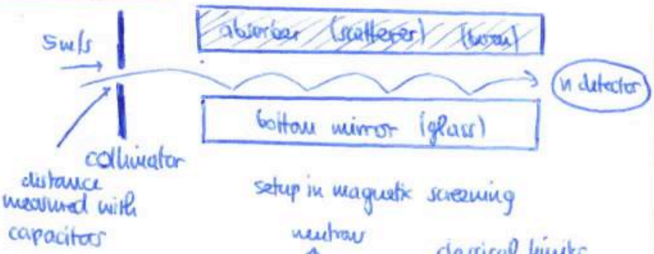
$$\left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2} + mgz\right)\varphi_n(z) = E_n \varphi_n(z)$$



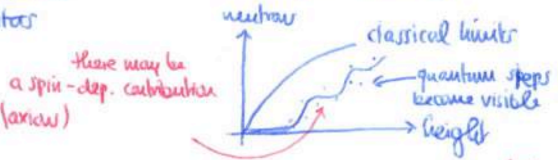
Neutrons ideal: neutral, long lifetime, low polarizability, elementary particles

→ characteristic length: $z_0 \sim 6\,\mu m$ (position of first max.)

State preparator:



setup in magnetic screening

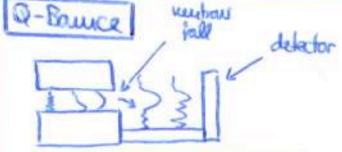


→ test non-Newtonian gravity at short (1-50 μm) distances: fifth force, extradimensions, chameleon dark energy, …

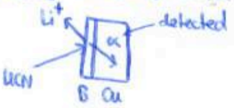
$$z_0 = \sqrt[3]{\frac{\hbar^2}{2 m_i m_g g}}, \quad E_0 = m_g g z_0$$

→ test weak equiv. principle in the quantum range

Q-Bounce



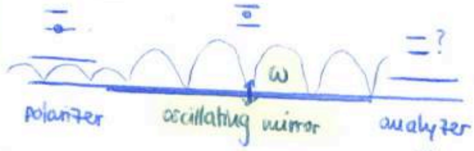
CR39 track detectors with Boron-10 conv.:



Evolution: $|\Psi(z,t)|^2 = \left|\sum_m d_m(t_0) e^{-i\omega_m t} \psi_m(z)\right|^2$

→ different eigenstates excited

Rabi setup:



Energy eigenstates: $E_k = m g z_0 \varepsilon_k$ ← dimensionless factor

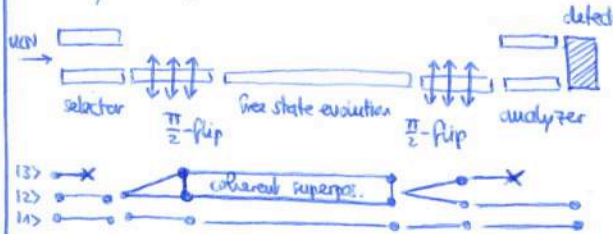
→ induce transitions between them:

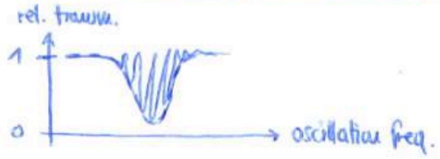
$$\delta\omega = \underbrace{\omega}_{\text{oscillating frequency}} - 2\pi\Delta f_{kl} \quad \text{decoherence}$$

$$\rightarrow P_{k\rightarrow l} = \frac{\sin^2\left(\sqrt{\delta\omega^2 + \Omega^2}\,\frac{t}{2}\right)}{1 + \frac{\delta\omega^2}{\Omega^2}}$$

Ω: oscillating strength (see p. 7)

Ramsey setup:





Motivation

- test of WEP in the quantum range
- search for non-Newtonian gravity at short distances (fifth force, …)
- dark matter

Variation of fundamental constants

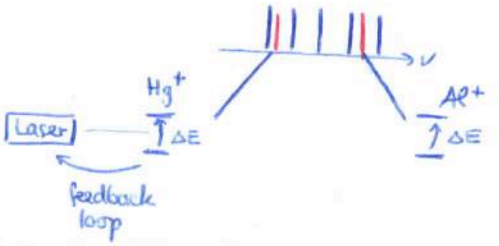
Measure atomic transitions and see if they vary with time
→ we need a reference: Cs HFS

$$\frac{d}{dt}\ln\left[\underbrace{\frac{\nu_{optical}}{\nu_{Cs}}}_{\text{optical vs. Cs transition}}\right] = (N_{optical}-N_{Cs}-2)\underbrace{\frac{\dot{\alpha}}{\alpha}}_{\text{variation of fine-structure constant}}+\dots$$

Alternatively: observe spectral line doublet from a quasar

Problem: $\frac{\Delta\nu^{Cs}}{\nu^{Cs}} \sim 10^{-15}$ while lasers $\sim 10^{-18}-10^{-20}$
→ we should redefine the second!

Here: stabilize laser comb to other transition



Al, Hg have different dependen. on α (alternatively: use two transitions of same atom)

Motivation first

When presenting an experiment, talk about the motivation first!

Variation of Systematics

Vary a systematical contribution to the measurem., extrapolate data to find value without this contribution.

Measure frequency

count maxima
count zero-crossings
do a fit

Uncertainty

$$125,26 \pm \underbrace{0,20\,(\text{stat})}_{\substack{\text{precision}\\ \to \text{no. of meas.}}} \pm \underbrace{0,08\,(\text{sys})}_{\text{accuracy}}\ \text{GeV}$$

Upper limit: typically 3σ level (expensive LHC experiments that can't be repeated: 5σ/6σ).

11. General Stuff