Low energy particle physics at PSI

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Future Colliders for Early-Career Researchers
The best description of the fundamental particles and their interactions

Very successful, developed in the last 50+ years

Still pending:
- Gravity is not included
- Dark matter and dark energy
- Matter-antimatter asymmetry
- Neutrino masses
- Naturalness and hierarchy problem

⇒ Need for some Beyond Standard Model (BSM) physics
Beyond Standard Model

Many models for BSM physics ...

R. Sundrum, Snowmass Theory Frontier 2022
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Intensity frontier $\Rightarrow$ PSI is the place to go
The High Intensity Proton Accelerator (HIPA) facility at PSI

Muon target stations TgM & TgE
7 beam lines for particle physics and materials science

Cockroft-Walton

Injecto"c" cyclotron

590 MeV cyclotron
2.4 mA, 1.4 MW
50 MHz

To spallation source SINQ

Proton therapy

Spallation source for ultracold neutrons nEDM experiment
The HIPA facility delivers high muon, pion and ultra-cold neutron (UCN) rates, allowing for a diverse research program:

- **cLFV searches:**
  - MEG II
  - Mu3e
  - PIONEER

- **EDM experiments:**
  - muEDM
  - n2EDM

- **Muonic atom spectroscopy:**
  - HyperMu
  - mu-Mass
  - MuX

- Many more (MuSun, muCool, nTRV, tauSPECT, etc.)
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Charged Lepton Flavor Violation

cLFV is possible in the SM, but not observable:

\[ B_{SM} \propto \left( \frac{\Delta m^2_{\nu}}{m_W^2} \right)^2 \approx 10^{-54} \]

The observation of a SM prohibited decay would give hint of BSM physics:

\[ B_{BSM} \propto \frac{1}{\Lambda^4} \]

At PSI two experiments measure such golden channels: MEG II and Mu3e.
Golden channels at PSI

MEG II
We require the coincidence of a $\gamma$ with a $e^+$:
- 2-body decay: kinematics model independent
- BKG: accidental coincidences + $\mu \rightarrow e\gamma\nu\nu$

Mu3e
We require the coincidence of 2 $e^+$ and 1 $e^-:
- 3-body decay: kinematics model dependent
- BKG: accidental coincidences + $\mu \rightarrow eee\nu\nu$
The aim is to improve the current limit of $\mathcal{B}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ (90% C.L.) to $\mathcal{B}(\mu \rightarrow e\gamma) < 6 \times 10^{-14}$ (90% C.L.)[1].
Mu3e detector

The aim is to improve the current limit of $\mathcal{B}(\mu \rightarrow eee) < 1.0 \times 10^{-12}$ (90% C.L.) to S.E.S. $< 10^{-16}$[2].
Electric dipole moment

Electric dipole moments violate CP symmetry.

\[ \mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} - d \frac{\vec{S}}{S} \cdot \vec{E} \]

muEDM and n2EDM strategy:
- polarize
- trap
- let precess
- measure the spin
Precession due to magnetic moment is cancelled by using the frozen spin technique: a radial electric field is applied to the trap.

\[ \vec{\omega} = -\frac{e}{m} \left\{ a \vec{B} + \left( \frac{1}{1-\gamma^2} - a \right) \vec{\beta} \times \vec{E} \right\} \left( \frac{1}{c} + \frac{\vec{\beta} \times \vec{B}}{c} \right) \]

\( \vec{\omega}_a \)

\( \vec{\omega}_e \)

\( N_u = \varepsilon_u N \)

\( N_d = \varepsilon_d N \)
The aim is to improve the current upper limit of $1.89 \times 10^{-19} \text{ e} \cdot \text{cm (90\% C.L.)}$ to $3 \times 10^{-21} \text{ e} \cdot \text{cm (90\% C.L.)}$ during phase I[3].
Measurement of Larmor frequency shift for polarity flip of electric field:

\[ hf_{L,\pm} = 2(\mu_n B_0 \pm d_n E) \sim 30 \text{ Hz} \]

Two main types of systematics are split into: induced by field inhomogeneities and correlation to electric field polarity.
The aim is to improve the current upper limit of $1.8 \times 10^{-26} \text{ e} \cdot \text{cm (90% C.L.)}$ to $1 \times 10^{-27} \text{ e} \cdot \text{cm (90% C.L.)}$[4].
Conclusions
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- low energy physics provides complementary information about BSM physics
- very active
- muons and neutrons are powerful probes for BSM (although not exclusive)
Thank you for your attention!

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- PSI Visitor’s Center
- A.-K. Perrevoort (Mu3e)
- N. Berger (stylish Feynman diagrams)
- MEG collaboration
- Anastasia Doinaki (muEDM)
- Vici Kletzl (n2EDM)
Conclusions

Resources


Back-up
Muon production

The protons impinge on the targets, producing pions that decay in muons. Depending on where they are created, we classify:

- Surface and sub-surface muons (5-30 MeV/c): they are created inside the target from pions at rest as a monochromatic line of 29.8 MeV/c of momentum. Therefore their energy depends only on their path inside the target. Additionally, they are fully polarized.

- Cloud muons: they come from pion decay in flight.

Due to the high intensity and low momentum, the most interesting muons for many experimental applications are surface muons: the HIMB project focuses on the transport of muons with a momentum around 28 MeV/c.