The 15th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon

Low-Energy Precision Physics at MESA

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The Mainz Microtron MAMI

Electron Accelerator for Fixed Target Experiments

$E_{\text{max}}$ (e-) = 1.6 GeV
$I_{\text{max}}$ ~ 100 µA (CW)

- Resolution $\sigma_E < 0.100$ MeV
- Polarization 85%
- Reliability: 7000 hours / year
The Mainz Microtron MAMI

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A1 electron scattering facility
A2 tagged photon beam facility
Mainz Energy-Recovering Superconducting Accelerator

Recirculating ERL

$E_{\text{max}} = 105/155$ MeV

$I_{\text{max}} > 1$ mA (ERL)

Commissioning 2022
Mainz Energy-Recovering Superconducting Accelerator

Recirculating ERL

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Commissioning 2022

Mode 1: Extracted Beam
P2 Experiment

Mark Pitt, Wednesday
Mainz Energy-Recovering Superconducting Accelerator

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Mark Pitt, Wednesday

Extracted beam
BDX Experiment

new building
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Commissioning 2022

Mode 1: Extracted Beam
P2 Experiment

Mode 2: ERL Internal Target

Mark Pitt, Wednesday

Extracted beam
BDX Experiment

new building
## MESA Physics Programme

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Internal Gas Target Experiment MAGIX in MESA ERL Mode
Operation of a high-intensity (polarized) ERL beam in conjunction with light internal target
→ a novel technique in nuclear and particle physics
→ measurement of low momenta tracks with high accuracy
→ competitive luminosities
MAinz Gas Internal EXperiment

Magnetic spectrometer
MAinz Gas Internal EXperiment

Magnetic spectrometer

TPC-based focal plane detector

- $10^{-4}$ momentum resolution
- Requires spatial resolution of 50 µm
- Open field cage
- GEM readout
MAnz Gas Internal EXperiment

Magnetic spectrometer

Cryogenic gas jet target

TPC-based focal plane detector
- 10^{-4} momentum resolution
- Requires spatial resolution of 50 µm
- Open field cage
- GEM readout
Supersonic Gas-Jet-Target

- Windowless!
- Supersonic gas jet
- Higher gas density ($10^{19}$/cm$^2$)
- Cryogenic
- H$_2$, $^3$He, $^4$He, O$_2$, …., Xe
- $O(10^{35}$ cm$^{-2}$ s$^{-1}$) @ $10^{19}$/cm$^2$
Supersonic Gas-Jet-Target

Commissioned in 2017/18 at A1/MAMI
Electromagnetic Form Factors at MAGIX
The Proton Radius Puzzle

Atomic Spectroscopy
(PSI: Lamb Shift in muonic hydrogen)

\[ R_E = 0.8409 \pm 0.0004 \text{ fm} \]

Nature (2012)
Science (2013)

Electron Scattering on proton
(EM form factor measurements)

\[ R_E = 0.879 \pm 0.008 \text{ fm} \]

PRL (2010)
PRD (2014)

Jan Bernauer, Wednesday
Proton Radius Puzzle - What is going on?

A worldwide effort in atomic physics, hadron/particle physics and theory

• New Physics explanation?
  Lepton – Non-Universality!
Different coupling of electron-proton vs. muon-proton
  → light or heavy new particles (Dark Photon)?

• Electron scattering expts.
  not at sufficiently low $Q^2$
  or – radiative corrections not understood
  or – normalization errors
  or .... ?

$$\left\langle r_{E/M}^2 \right\rangle = -\frac{6\hbar^2}{G_{E/M}(0)} \frac{dG_{E/M}(Q^2)}{dQ^2} \bigg|_{Q^2=0}$$
The Quest for Low-$Q^2$ Scattering Data

- MAMI ISR (Proposal 2017)
- Data until 1980
- Bernauer (MAMI 2010)
- Belushkin (Dispersion Analysis 2007)
The Quest for Low-$Q^2$ Scattering Data

- MAGIX at MESA $E_0 = 20$ MeV
- MAGIX at MESA $E_0 = 45$ MeV
- MAGIX at MESA $E_0 = 105$ MeV
- MAMI ISR (Proposal 2017)
- Data until 1980
- Bernauer (MAMI 2010)
- Belushkin (Dispersion Analysis 2007)

Eugene Pasyuk, Monday
Magnetic Form Factor @ MAGIX

\[ \frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{Mott} \frac{1}{\varepsilon (1 + \tau)} \left[ \varepsilon G_E^2 (Q^2) + \tau G_M^2 (Q^2) \right] \]

\[ \tau = \frac{Q^2}{4m_p^2} \]

\[ \varepsilon = \left( 1 + 2 (1 + \tau) \tan^2 \frac{\theta_e}{2} \right)^{-1} \]

Low Q² accessible with low E_{beam}

Suppressed at low Q² due to \( \tau \)

→ Double polarization measurement

Beam Target Asymmetry!

### Beam Spin

### Target Spin

\[ \phi^* = 0 \]
\[ \theta^* = 0, \pi/2 \]

⇒ \( A_\perp \sim \frac{G_E}{G_M} \)
Magnetic Form Factor @ MAGIX

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\[ \Rightarrow A_\perp \sim \frac{G_E}{G_M} \]
Proton Radius Puzzle - What is going on?

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• Unknown QED / hadronic correction in $\mu$H data?

![Diagram showing various corrections and uncertainties in the measurement of the proton radius.](chart.png)

- 1-loop eVP
- proton size
- 2-loop eVP
- $\mu$SE and $\mu$VP
- discrepancy
- 1-loop eVP in 2 Coul.
- recoil
- 2-photon exchange
- hadronic VP
- proton SE
- 3-loop eVP
- light-by-light

largest hadronic correction/uncertainty: $\Delta E_{2\nu} = (33 \pm 2) \mu$eV
Polarisability Corrections in Light Nuclei Systems

\[ \mu_H: \Delta E^{TPE}_{2P - 2S} = (33 \pm 2) \mu eV \]
dispersive analysis

Carlson, Vanderdhaeghen (2011)
accuracy comparable with present experimental precision
\rightarrow Related to proton polarizability

Edoardo Monarcchi, Monday
Polarisability Corrections in Light Nuclei Systems

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\( \mu^D: \Delta E^{\text{TPE}} = (1727 \pm 20) \mu\text{eV} \)

nucleon potentials form chiral EFT

Hernandez et al. (2014)

accuracy factor 5 worse than present experimental precision

\( \mu^3\text{He}^+: \Delta E^{\text{TPE}} = (15.46 \pm 0.39) \text{meV} \)

nucleon potentials form chiral EFT

Nevo Dinur, Ji, Bacca, Barnea (2016)

\( (15.14 \pm 0.49) \text{meV} \) dispersive analysis

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**Polarisability Corrections in Light Nuclei Systems**

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Lots of opportunities at MAMI/MESA for measurements of proton polarizabilities and in the field of few-body physics
Light
Dark Sector
Searches
Dark Sector Searches

- keV  MeV  GeV  TeV  DM Mass

LDM

Dark Photon - Messanger
New massive force carrier of extra $U(1)_d$ gauge group

- Could explain large number of astrophysical anomalies
Arkani-Hamed et al. (2009)
Andreas, Ringwald (2010);

- Could explain deviation of 3.7σ between $(g-2)_{\mu}$ SM prediction and direct $(g-2)_{\mu}$ measurement
Pospelov (2008)
Dark Sector Searches

keV  MeV  GeV  TeV  DM Mass

DM Mass

WIMPs

WIMP mass vs. WIMP-nucleon cross section.
Dark Photon

Model 1: \( m_{\gamma'} \ll m_{DM} \)

Dark Photon decaying into SM particles – coupling \( \epsilon \)

Holdom [1986]
Dark Photon

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**Dark Photon**

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```latex
\begin{align*}
\text{Model 1: } & m_{\gamma'} \ll m_{DM} \\
\text{Dark Photon decaying into SM particles – coupling } & \epsilon 
\end{align*}
```

**Model 2:** \( m_{\gamma'} > 2m_{DM} \)

Dark Photon decaying into Dark Matter

\( \rightarrow \) invisible decay experiments

\( \rightarrow \) LDM detection

```latex
\begin{align*}
\text{Model 2: } & m_{\gamma'} > 2m_{DM} \\
\text{Dark Photon decaying into Dark Matter } & \rightarrow \text{invisible decay experiments} \\
& \rightarrow \text{LDM detection}
\end{align*}
```

Holdom [1986]
Results from A1 / MAMI

Model 1: \( m_{\gamma'} \ll m_{\text{DM}} \)

Low-Energy Electron Accelerators with high Intensity ideally suited for Dark Photon search (Bjorken et al.)

Signal process

Hypothetical Dark Photon signal: bump in one single bin

QED bkg.
Results from A1

- \( E_{\text{beam}} \) 180 - 855 MeV
- 100 \( \mu \)A beam current
- Stack of Ta targets
- 22 kinematic settings
- \( O(1 \text{ month}) \) of beam time

\( \rightarrow \) at time of publication most stringent limit ruling out major part of the parameter range motivated by \((g-2)_\mu\)
Features:

- Xe gas target
- Luminosity $10^{35}$ cm$^{-2}$s$^{-1}$
- 6 month of data taking
Model 2: \( m_{\gamma'} > 2m_{DM} \)
Model 2: \( m_{\gamma'} > 2m_{DM} \)

Species from Collimated pair of Dark Matter particles!
Simulation BDX @ MESA

Full GEANT4 simulation:
P2 target, beam dump, BDX detector volume, walls etc.

→ LDM interaction with BDX material (electron recoil)

\[ E_{\text{beam}} = 140 \text{ MeV} \]
\[ \chi \text{ elastic scattering kinematics} \]

Achim Denig
Detector Concept for BDX @ MESA

Ideal Requirements:
1. Electron Detection > few MeV
2. Large Surface (Acceptance)
3. Large thickness (Int. Prob.)
4. Reliability (long running time)
5. Background rejection
   - Cosmics
   - Natural Backgrounds
   - Beam Backgrounds (Neutrons)

Baseline Concept
Inorganic crystal calorimeter
- Cherenkov (fast, no neutrons)
- Scintillator (higher light yield)
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**Beam Dump Experiment (BDX) @ MESA**

**Detector layouts:**
- **Phase A**
  - PbF$_2$
- **Phase B**
  - Lead glass
  - 0.13 m$^3$
- **Phase C**
  - Lead glass
  - ~ 10 m$^3$
Conclusions

- **New MESA electron accelerator** (increase in intensity x 10) under construction at Mainz, commissioning in 2022

- **The low-energy frontier:**
  - Proton Radius
  - EW Mixing Angle
  - Dark Sector
  - Nuclear Astrophysics
  - Few Body Physics
  - ....

- **Projection for MESA based on experiences achieved at MAMI**

- Go beyond state of the art in many **technological aspects:** ultralight detectors, beam polarization, low energy detection, ...

- **Competitive programme in nuclear, hadron, and particle physics**
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