Search for the X17 particle with the MEG-II apparatus

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on behalf of the MEG-II collaboration

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The Beryllium Anomaly

**Atomki Experiment**

\[ \text{\( p^+ \rightarrow \)} \text{\( 7\text{Li} \)} \]

\[ \text{\( 7\text{Li}(p, e^+ e^-) \rightarrow \)} \text{\( 8\text{Be} \)} \]

\[ \Theta \approx 140^\circ \]

\[ E_p = 450, 650, 800, 1100 \text{ keV} \]

\[ e^+ / e^- \text{ energy sum and angular correlation } \Theta \]

**2022 Atomki results**

- **Internal Pair Conversion (IPC)** distribution shows excess at \( \Theta \approx 140^\circ \) at several beam energies
- 1 possible explanation: decay of a light particle emitted during proton capture

- best fit \( m_X = 16.95 \text{ MeV/c}^2 \)
- \( BR(X) = 6 \times 10^{-6} \)
- protophobic vector boson X17? mediator of a fifth force?

**EPC = External Pair Conversion**

\( \rightarrow \gamma \text{-conversion in matter} \)

**IPC = Internal Pair Conversion**

\( \rightarrow \text{direct } e^+/e^- \text{ pair creation} \)

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Background + signal

Data

Wrt to \( \gamma \) production

arXiv:2205.07744

Phys. Rev. D 95, 035017

22-08-2023

ISMD 2023, Gyöngyös

The X17 search with MEG-II

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Standard physics or new boson?

The X17 search with MEG-II

- Excess in IPC background at 115° angular opening: >6σ
- Possible explanation: a 16.84 MeV neutral boson (X17?)
- Other indirect searches (NA64, NA48/2): no evidence for X17 but strong constraints

Phys. Rev. D, 101:071101

- Can the measurement be performed with an independent setup, the MEG-II apparatus?
MEG-II objectives

• Hint for the production of a neutral, 17 MeV boson, potential mediator of a fifth force: X17

• Need for experimental confirmation: MEG-II has all elements to carry out the measurement
  ⏯ Improved resolution
  ⏯ Reconstruction in full solid angle
  ⏯ Reproduction of excess?

• Engineering run in 2022
• X17 physics run was taken by MEG-II in February 2023
Apparatus
The MEG-II experiment

- MEG-II experiment searches for charged lepton flavour violating decay: $\mu \rightarrow e\gamma$
- 1 order of magnitude sensitivity improvement wrt MEG: $BR(\mu \rightarrow e\gamma) \rightarrow 6 \times 10^{-14}$

The new MEG-II highly performing spectrometer can be used for X17-boson search:
- X17-dedicated target in place of the muon target
- MEG-II CW accelerator as proton beam
- adjusted magnetic field
- gamma auxiliary detectors
- optimized TDAQ
The Cockcroft-Walton accelerator

- **LXe calibration**
  - MEG-II Cockcroft-Walton accelerator: used for calibration of LXe calorimeter
  - Proton beam impinging on Li target (440 keV resonance): 17.64 MeV $\gamma$ line

- **X17 search**
  Max proton current and energy: 100 $\mu$A and 1.1 MeV
  - ideal for X17 search (1 MeV resonance and 18.15 MeV $\gamma$ line)

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**p+Li cross-section**

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**LXe calibration**

**X17 search with MEG-II**

**Anomaly found by ATOMKI over the whole range**
The new target region

- Main target for physics run
  - 2 μm LiPON\(^(*)\) on 25 μm copper substrate (by PSI)
- For gamma detectors calibration
  - 5 μm LiF on 10 μm copper substrate (by INFN Legnaro)
- Target-supporting and heat-dissipating copper structure attached to CW nose
- 400 μm-thick carbon fiber vacuum chamber to minimize multiple scattering

**Li target**
- at COBRA center
- 45° slant angle

**Target arm**
- Cu for heat dissipation

**Carbon fiber vacuum chamber**
- Thickness: 400 μm, Diameter: 98 mm
- Length: 226 mm

\(^(*)\) Lithium phosphorus oxynitride (Li\(_{3-x}\)PO\(_{4-y}\)N\(_{x+y}\))

**Li distribution in target under investigation**

**B field x0.15 wrt MEG**
(0.2T at center)
Gamma detectors

- Main gamma detector for bkg understanding: **LXe calorimeter**
- Two additional gamma detectors for monitoring:
  - **BGO crystal matrix (4x4)**
  - **LaBr3 crystal**

Liquid Xenon Calorimeter (XEC)

**LiPON spectrum from XEC**

- Energy levels:
  - Ground state: 0 MeV
  - 1st excited state: 3.05 MeV
  - To ground state: 17.64 MeV
  - To 1st excited state: 14.59 MeV

**Graph**

- **Energy levels:**
  - 18.15 MeV
  - 17.64 MeV
- **Spin & Parity:**
  - SPIN-1 PARITY-EVEN
- **Type of Transition:**
  - (M1 = MAGNETIC, p-WAVE)

**Legend**

- CDCH + pTC
- BGO
- LaBr3

**Equation**

\[ E_p = 500 \text{ keV} \]
2022 engineering run
• With all elements mentioned above, engineering run in February 2022

• Take-aways from 2022 run
  ➔ converting gammas from 6 MeV Fluorine line overcrowd the trigger (LiF target)
  —> LiPON has to be used for X17 search
  ➔ CDCH multiplicity condition (18 hits) strongly suppresses trigger contamination and improves reconstruction
  ➔ target region can stand high proton currents (up to 10uA) without overheating
  —> heat-dissipating material can be reduced (less EPC background)
• **MEG-II only reconstructs e+.** Procedure was adapted for e- as well.

- **Procedure**
  - All tracks in an event are propagated to the beam axis POCA.
  - If 1 e+ track and 1 e- track pass the quality selection, a pair is found.
  - Energy sum \( E_{\text{sum}} = E_+ + E_- \) and opening angle are computed.

- **IPC Monte-Carlo** for both 18 and 15 MeV lines was produced based on **Zhang–Miller model**


- **LiPON event**
  - \( p^+ \) at target
  - \( p^- \) at target
  - \( e^+ \) hit
  - \( e^- \) hit
  - target

- **MC simulation**
  - 18 MeV IPC

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2023 physics run and analysis strategy
• In February 2023, X17 physics run for 4 weeks at $E_p = 1080$ keV

• X17 runs: sample of 25k runs of 3k events each
  → 75M triggered events
  → 300k pairs to be reconstructed

On full $E_{\text{sum}}$ and Angular Opening range:
  → 60% EPC (15+18)
  → 40% IPC (15+18)

• DOMINANT AT LOW ANGLES
• NEGLIGIBLE IN SIGNAL REGION

• DOMINANT BACKGROUND IN SIGNAL REGION

Background PDFs in development
Analysis strategy

- **2D likelihood maximization:** \( E_{sum} \) vs Angular Opening

- **Blinded signal region** defined as:
  - \( 16 \text{ MeV} < E_{sum} < 20 \text{ MeV} \)
  - \( 115^\circ < \text{Angle} < 160^\circ \)

- Before unblinding, understanding of background will be done in two sidebands
  - **Angle sideband**
    - \( 16 \text{ MeV} < E_{sum} < 20 \text{ MeV} \)
    - \( 0^\circ < \text{Angle} < 115^\circ \)
  - **\( E_{sum} \) sideband**
    - \( 14 \text{ MeV} < E_{sum} < 16 \text{ MeV} \)
    - Full angle range

**MC simulation**
E_{\text{sum}} \text{ sideband: } 14 \text{ MeV} < E_{\text{sum}} < 16 \text{ MeV}

<table>
<thead>
<tr>
<th>Entries</th>
<th>Mean</th>
<th>Std Dev</th>
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<tbody>
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<td>4075</td>
<td>37.68</td>
<td>24.02</td>
</tr>
</tbody>
</table>

- 14 MeV < E_{\text{sum}} < 16 MeV
- Full angle range

Normalized entries

--> monotonously decreasing IPC tail

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The X17 analysis

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Reconstruction in non-orthogonal planes

Efficiency wrt to X17 production [%] includes trigger, detector acceptance and reconstruction

- X17 reconstructed not only in orthogonal plane
- 1% efficiency in planes between 40° and 140°
• Based on ATOMKI results:

\[ BR(X) = 6 \times 10^{-6} \text{ wrt to } \gamma \text{ production} \]

\[ BR(\text{IPC}) = 3 \times 10^{-3} \text{ wrt to } \gamma \text{ production} \]

• From 2023 full dataset

\[ O(400 \times 17) \]
• 2022 engineering run and 2023 physics run **DONE**

• Pair reconstruction and track selection **READY**

• Reprocessing of 2023 data **ONGOING**

• Sidebands checks **ONGOING**

• Building background PDFs **TO BE STARTED**

• Unblinding **TO BE DONE**

In parallel: lithium distribution on 2023 target — uniformity and depth — will be investigated
Conclusion and outlook

• Anomalous excess observed in the angular correlation of $^7\text{Li}(p, e^+ e^-)^8\text{Be}$ by the Atomki collaboration

• The MEG-II collaboration has designed, tested and built all the elements to perform the X17 search in an independent manner
  ➔ better understanding of the X17 anomaly

• 4-week physics runs in February 2023
  ➔ pair reconstruction procedure ready
  ➔ blinded analysis strategy:
    $2D \, E_{\text{sum}} \, \text{vs} \, \text{Angle}$ likelihood maximization
    ➔ 2023 reprocessing, sidebands checks ongoing
  ➔ PDFs construction and unblinding coming up
Thank you for your attention!

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Backup slides
Reduced magnetic field and beam tuning

• $\mu \rightarrow e\gamma$ search relies on 52.8 MeV positron search with default magnetic field (1.27T at COBRA center)

• for X17: energies $\sim 6$ times lower $\rightarrow$ scaling of the field by a factor 0.15

• CW tuned using a quartz target: proton-induced fluorescence in the quartz, visible emission

• Tuning made varying 3 dipolar fields along the beamline to center the beam $\rightarrow$ beam spot centered and covering the Li area

megCam - COBRA OFF
CCD camera - COBRA ON
Gamma detectors

• Two additional gamma detectors
  ➡ Stability monitoring  ➡ Signal normalisation  ➡ Daily monitoring

Bismuth Germanate (BGO) crystal matrix (4x4)

Lanthanum Bromide (LaBr3) crystal

Gamma rate in BGO per current unit [Hz/μA]
Angle sideband: angle < 115°

- 0° < Angle < 115°
- 16 MeV < Esum < 20 MeV

- IPC dominant over 80°
- Background shapes to be refined with higher statistics MC

5% of 2023 data are used here

→ angular acceptance data and MC to be compared
LiF spectrum