Searching for X17 with the PADME experiment



Mauro Raggi for the PADME collaboration, Sapienza Università di Roma e INFN Roma The X(17) saga Sapienza 17/04/2023

The dark sector paradigm



- Dark sector candidates can explain SM anomalies: (g-2)μ, ⁸Be, proton radius
- The mediator can have a small mass (MeV -100 MeV)
- Due to its small mass the mediator can be produced at low energy accelerators
- It can decay back to ordinary matter "visible" on not "invisible"



Experimental approaches

- Electron beam experiments production
 - Just A'-strahlung
- Positron based experiments
 - A'-strahlung
 - Associated production $e^+e^- \rightarrow A'(\gamma)$
 - Resonant production $e^+e^- \rightarrow e^+e^-$
- Visible decays: $A' \rightarrow e^+e^- A' \rightarrow \mu^+\mu^-$
 - Thick target electron/protons beam is absorbed (NA64, old dump experiments)
 - Thin target searching for bumps in ee invariant mass
- Invisible searches: $A' \rightarrow \chi \chi$
 - Missing energy/momentum: A' produced in the interaction of an electron beam with thick/thin target (NA64/LDMX)
 - Missing mass: $e^+e^- \rightarrow A'(\gamma)$ search for invisible particle using kinematics (Belle II, PADME)



Brems.





Mauro Raggi, Sapienza

PADME Run I and Run II setup

- Positron beam of ~0.5 GeV/c
 - LINAC repetition rate 50 Hz
 - Macro-bunches maximum length $\Delta t \leq 300$ ns
- Number of annihilations proportional to:

 $N_{beam}^{e^+} \times N_{target}^{e^-}$

- Limited intensity, due to pile-up, ~3.104 pot/pulse
- Dipole magnet in order to
 - Sweep away non-interacting positrons
 - Tag positrons losing energy by Bremsstrahlung
- Scintillating bar veto detectors placed inside vacuum vessel
 - Positron and electron detectors inside the magnet gap
 - Additional veto for e⁺ irradiating soft photons at beam exit



BGO calorimeter (ECAL)



PADME data taking periods



- Two physics runs Run I Oct. 2018 Feb. 19 and Run II Set-Dec 2020
 - Hard simulation work to understand BG in between Run I and Run II.
- Run II wrt Run I
 - Slightly lower beam momentum in Run II, 430 MeV/c, wrt to Run I, 490 MeV/c
 - Improved vacuum separation between experiment and beamline
 - Less beam-induced background with primary wrt secondary beam
- During Run II itself
 - Improved bunch length and structure





PADME $\sigma(e^+e^- \rightarrow \gamma\gamma)$ result in Run II



The ⁸Be and ⁴He Atomki anomaly



ATOMKI has confirmed the anomalous peak in the angular distribution of internal pair creation in ⁸Be with a similar one in the ⁴He transitions, with different kinematics but at the same invariant mass value.



The ¹²C anomaly and the vector portal

New anomaly observed in ¹²C supports the existence and the vector character of the hypothetical X17 boson ArXiv:2209.10795v1



TABLE I. X17 branching ratios (B_x) , masses, and confidences derived from the fits.

\mathbf{E}_{p}	B_x	Mass	Confidence
(MeV)	$\times 10^{-6}$	(MeV/c^2)	
1.5	2.7(2)	16.62(10)	8σ
1.7	3.3(3)	16.75(10)	10σ
1.88	4.1(4)	16.94(10)	11σ
2.1	4.7(9)	17.12(10)	6σ
Averages	3.4(3)	16.86(17)	
Previous [1]	5.8	16.70(30)	
Previous [21]	5.1	16.94(12)	
Predicted [16]	3.0		

4 different bombarding energies with strong significance







Direction in searching for X17

SAPIENZA Università di Roma



9

Current constraints on X17 from leptons



X17 as a vector particle:

- LKB (g-2)_e bound weaker for vector and model dependent
- NA48/2 bound not valid for "protophobic" X17
- Still a lot of free parameter space for vector X17

Phys. Rev. D 104, L111102 (2021)



X17 as pseudo scalar particle:

- (g-2)_e bound stronger for pseudo scalars
- Still model dependent and with big data uncertainties
- Almost unconstrained parameter space for X17

On the nature of X17

PHYSICAL REVIEW D 102, 036016 (2020)

Dynamical evidence for a fifth force explanation of the ATOMKI nuclear anomalies

Jonathan L. Feng[®],^{*} Tim M. P. Tait[®],[†] and Christopher B. Verhaaren^{®[‡]} Department of Physics and Astronomy, University of California, Irvine, California 92697-4575, USA

Feng and collaborators suggested that the X17 should be observed in ¹²C transitions X17 observations in ¹²C will point to a vector or axial vector nature for X17

TABLE III. Nuclear excited states N_* , their spin-parity $J_*^{P_*}$, and the possibilities for X (scalar, pseudoscalar, vector, axial vector) allowed by angular momentum and parity conservation, along with the operators that mediate the decay and references to the equation numbers where these operators are defined. The operator subscripts label the operator's dimension and the partial wave of the decay, and the superscript labels the X spin. For example, $\mathcal{O}_{4P}^{(0)}$ is a dimension-four operator that mediates a *P*-wave decay to a spin-0 X boson.

N_*	$J^{P_*}_*$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
⁸ Be(18.15)	1+		$\mathcal{O}_{4P}^{(0)}$ (27)	$\mathcal{O}_{5P}^{(1)}$ (37)	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)
$^{12}C(17.23)$	1-	${\cal O}_{4P}^{(0)}$ (27)		$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)	$\mathcal{O}_{5P}^{(1)}$ (37)
4 He(21.01)	0^{-}		$\mathcal{O}_{3S}^{(0)}$ (39)		$\mathcal{O}_{4P}^{(1)}$ (40)
⁴ He(20.21)	0^+	${\cal O}_{3S}^{(0)}$ (39)		$\mathcal{O}_{4P}^{(1)}$ (40)	



PADME X17 searches on Run II data





Final state $e^+e^- \rightarrow X_{17}\gamma \rightarrow e^+e^-\gamma$

- Use radiative return E_{beam} =430 MeV
- small contribution from γγ
- Large beam γ background reducing the sensitivity

Try to identify pairs of leptons using PADME veto

- Large BG from BhaBha scattering
- Large beam background increasing combinatorics BG
- Lepton invariant mass not accessible





How can we make our life easier?



$$\mathcal{N}_{X_{17}}^{\text{Vect.}} \simeq 1.8 \cdot 10^{-7} \times \left(\frac{g_{ve}}{2 \cdot 10^{-4}}\right)^2 \left(\frac{1 \text{ MeV}}{\sigma_E}\right) \qquad \qquad \mathcal{N}_{X_{17}}^{\text{ALP}} \simeq 5.8 \cdot 10^{-7} \times \left(\frac{g_{ae}}{\text{GeV}^{-1}}\right)^2 \left(\frac{1 \text{ MeV}}{\sigma_E}\right)$$



The mass scan X17 search strategy

PADME, can use resonant X17 production process

- Extremely effective in producing X17 but in a very small mass range
- Scan E_{beam}=260–300 MeV in ~1.5 MeV steps
- Need only ~10¹⁰ POT per point
- Signal should emerge on top of Bhabha BG in one point of the scan.
- Critical parameter for signal to background optimization: beam energy spread





Bhabha scattering



|**p**| [(

PADME expected sensitivity

L. Darmé, M. Mancini, E. Nardi, M.R. Darmé et al. Phys. Rev. D 106,115036



- BG from SM Bhabha scattering under control down to ε = few 10⁻⁴
 - Challenge is to achieve an extremely precise luminosity measurement and systematic errors control
 - PADME maximum sensitivity in the vector case



PADME Run III modified setup

- PADME veto spectrometer is hard to reconstruct $e^+ e^-$ mass having no vertex detector
- Idea: identify $e^+e^- \rightarrow e^+e^-$ using the BGO calorimeter, as for $\gamma\gamma$ events in Run II
- Switch the magnet off
- Both positron and electron will reach the ECal
 - Can measure precisely (3%) electron-positron pair momentum and angles
 - Can reconstruct invariant mass of the pairs precisely (small pile-up)
- Identify clusters in ECal from photons or electrons
 - New detector, plastic scintillators, similar to PADME vetos (Electron tagger, ETag) with vertical segmentation and covering the fiducial region of ECal



- Thanks to the enhanced production cross section can reduce N_{POT}/bunch by factor 10.
- Much lower pile-up and better energy resolution



Left/Right ETag bar

1500

1000 500

0.8

Padme Run III data

Covers a region of 2σ in mass around the predicted region by Atomki Collected 47 points at different energy

The collected statistics is enough to enter the NA64 coupling limit.

The precision on the mass measurement will be: (17.3-16.3)/47 ~ 22 KeV



 $\theta_{clus}[mRad]$ pair Background on off resonance 2000 data is under control 1400 600 1200 1000 0.04 0.03 400 200 0.02 Eclus [MeV] $\Delta t_{clus}[ns]$



X17 observables at PADME

$$\frac{N(e^+e^-)}{N^{PoT}} VS \sqrt{S} \qquad \frac{N(\gamma\gamma^-)}{N^{PoT}} VS \sqrt{S}$$
Osservabili
$$\frac{N(e^+e^-+\gamma\gamma)}{N^{PoT}} VS \sqrt{S}$$

$$\frac{N(e^+e^-)}{N(\gamma\gamma)} VS \sqrt{S}$$

Several different observables can be used with different:

- N(2cl)/N_{Pot} = existence of X_{17}
- N(2e)/N(2 γ) = existence of X₁₇
- N_{e+e-}/N_{PoT} = vector nature of X_{17}
- $N_{\gamma\gamma}/N_{Pot}$ = pseudo-scalar nature of X_{17}



Conclusions

- PADME performed two physics runs, collecting ~5.10¹² POT each
- Run II data-set, collected during the pandemics, with primary positron beam showed much better background conditions than Run I
- The detectors are performing very well, a reliable Monte Carlo simulation, including the beamline, is also available
- PADME delivered its first physics result
 - $\sigma(e^+e^- \to \gamma\gamma) = (1.977 \pm 0.018_{stat} \pm 0.119_{syst}) \text{ mb}$
 - 5% precision, best measurement below 1 GeV
 - Can constrain pseudo-scalar dark sector candidates
 - A step towards the invisible dark photon analysis
- PADME Run III is ongoing and will address the X17 anomaly, trying to significantly impact the vector portal scenario.









Obtaining energy steps and resolution



Use the first dipole magnet and collimators to select energy

• dp \propto collimator aperture.

Change the first dipole magnet current to change the energy

Correct the trajectory using second dipole to put the beam back on axis at PADME

Measure the displacement at the target and timePix to measure the energy step performed



g-2e anomaly

- Significant discrepancy in the last two results on the α determination
- Produce a modified (g-2)_e exclusion which allows a region of existence of X17



 $\alpha^{-1} = 137.035999206(11).$



The uncertainty contribution from the ratio $h/m(^{87}\text{Rb})$ is 2.4×10^{-11} (statistical) and 6.8×10^{-11} (systematic). Our result improves the

https://www.nature.com/articles/s41586-020-2964-/

experimental measurement $a_{e,exp}$ (ref. ⁹) gives $\delta a_e = a_{e,exp} - a_e(\alpha_{LKB2020})$ = (4.8 ± 3.0) × 10⁻¹³ (+1.6 σ), whereas comparison with caesium recoil measurements gives $\delta' a_e = a_{e,exp} - a_e(\alpha_{Berkeley}) = (-8.8 \pm 3.6) \times 10^{-13} (-2.4\sigma)$. The uncertainty on δa_e is dominated by $a_{e,exp}$.

Muon g-2 anomaly



g-2 and A'





g-2 in the standard model



About 3σ discrepancy between theory and experiment (3.6 σ , if taking into account only e+e->hadrons)

Contribution to g-2 from dark photon

Additional diagram with dark photon exchange can fix the discrepancy (with sub GeV A' masses)

$$a_{\mu}^{\text{dark photon}} = \frac{\alpha}{2\pi} \varepsilon^2 F(m_V/m_{\mu}), \qquad (17)$$

where $F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2z] dz$. For values of $\varepsilon \sim 1-2 \cdot 10^{-3}$ and $m_V \sim 10$ -100 MeV, the dark photon, which was originally motivated by cosmology, can provide a viable solution to the muon g-2 discrepancy. Searches for the dark