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Experiments on 8Be IPC at INFN Legnaro Laboratory

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Shedding light on X17 Rome 04/09/2021





# Outline

- Motivation and interest on the "X17 case"
- LNL's low-energy facilities
- Aipac8Be: a new setup at LNL for IPC studies
- Conclusion and outlook



## Motivation: renewed interest on IPC.





**The reaction:** <sup>7</sup>**Li(p,e**<sup>+</sup>e<sup>-</sup>)<sup>8</sup>**Be** allows to selectively populate the 17.64 MeV and 18.15 MeV resonances. The considered transitions are M1 type. Isospin is assigned in analogy to isobaric

nuclei -> two iso-scalar and two iso-vector transitions.







 $^{7}$ Li(p,e<sup>+</sup>e<sup>-</sup>)<sup>8</sup>Be

a):  $E_p = 1.20 \text{ MeV}$ b):  $E_p = 1.10 \text{ MeV}$ 

c):  $E_{n}^{P} = 1.04 \text{ MeV}$ 

d):  $E_{n}^{r} = 0.80 \text{ MeV}$ 

120

140

 $\times 10$ 

160

[A. J. Krasznahorkay et al, Phys Rev Lett 116, 042501 (2016)]

PRL 116, 042501 (2016)

PHYSICAL REVIEW LETTERS

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#### Observation of Anomalous Internal Pair Creation in <sup>8</sup>Be: A Possible Indication of a Light, Neutral Boson

A. J. Krasznahorkay,\* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár,



FIG. 4. Experimental angular  $e^+e^-$  pair correlations measured in the <sup>7</sup>Li( $p, e^+e^-$ ) reaction at  $E_p = 1.10$  MeV with  $-0.5 \le y \le 0.5$  (closed circles) and  $|y| \ge 0.5$  (open circles). The results of simulations of boson decay pairs added to those of IPC pairs are shown for different boson masses as described in the text.

FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in <sup>8</sup>Be.

The deviation between the experimental and theoretical angular correlations is significant and can be described by assuming the creation and subsequent decay of a  $J^{\pi}=1^+$  boson with  $m_0c^2=16.70\pm0.35(\text{stat})\pm0.5(\text{syst})$  MeV/ $c^2$ . The branching ratio of the  $e^+e^-$  decay of such a boson to the  $\gamma$ -decay of the 18.15 MeV level of <sup>8</sup>Be was found to be  $5.8\times10^{-6}$  for the best fit.

Such a boson might be a good candidate for the relatively light  $U(1)_d$  gauge boson [4], or the light mediator of the secluded WIMP dark matter scenario [5] or the dark Z (Zd) suggested for explaining the muon anomalous magnetic moment [7].

F.W. N. de Boer et al, Phys Lett B 388, 235 (1996) F.W. N. de Boer et al, J. Phys G: Nucl Part Phys 23, L85 (1997) F.W. N. de Boer et al, J Phys G: Nucl Part Phys 27, L29 (2001) And several others.

> dedicated experiments are reported yielding <mark>further</mark> indications for an anomaly at 9 MeV/c2 Results of two correlation of IPC. The first experiment (8Be) shows a deviation from IPC at in the anaular large correlation angles presumably due to the same anomaly in the transition to the first excited state. The second experiment (12C) shows a relatively large anomaly at 9 MeV/c2, albeit with limited statistics. Both results are compatible with an X-boson scenario where the boson-nucleon coupling strength is proportional to the isoscalar strength in the M1 transition. Exploiting isospin structure as a guideline, further high statistics experiments are needed to establish the nature of the anomaly.

**Table 1.** Experimental results relevant for the search of anomalous  $e^+e^-$  production in nuclear transitions with respect to IPC, in the invariant mass range from 5 to 15 MeV/c<sup>2</sup>. Listed are the nucleus, the quantum numbers, the energy (*E*) and character (E1, M1) of the transition, the derived boson emission branching ratio (*B<sub>X</sub>*) with respect to  $\gamma$  emission, the boson decay width ( $\Gamma_X$ ), the isospin dependent effective coupling strength ( $\alpha_X$ ), relative to  $\tilde{\alpha} = 1.7 \times 10^{-6}$  (the axion–nucleon coupling strength), the invariant mass  $m_X$  and the literature references. Values for  $B_X$  and  $\Gamma_X$  have been derived at 95% CL.

$^{A}Z$	Ιπ	Т	E MeV	$B_X$	$\Gamma_X$ meV	$lpha_X$ $1.7  imes 10^{-6}$	$m_X$ MeV/c <sup>2</sup>	Reference
<sup>20</sup> Ne	1-	1	17.8 E1 16.2 E1	$\leqslant 1.3  imes 10^{-4}$	≤ 3	≤ 1.8		[20]
<sup>12</sup> C	$\frac{1^{-}}{2^{-}}$	1 1	17.2 E1 12.3 E1	$\leqslant 2.3 \times 10^{-5}$	$\leq 1$	<b>≼</b> 0.3		[1]
<sup>12</sup> C <sup>12</sup> C <sup>12</sup> C <sup>8</sup> Be	$1^+$ $1^+$ $1^+$	$\begin{pmatrix} 0 \\ 1 \\ 1 \\ 0 \end{pmatrix}$	12.7 M1 15.1 M1 114 M1 17.6 M1	$(1.6 \pm 0.7) \times 10^{-3} \\ \leqslant 4.6 \times 10^{-5} \\ \leqslant 9.8 \times 10^{-5} \\ (11.4 \pm 3.4) \times 10^{-5}$	$0.55 \pm 0.24 \le 1.7 \le 8$ 1.9 ± 0.4	$38 \pm 17 \\ \leqslant 0.9 \\ \leqslant 0.8 \\ 1.5 \pm 0.4$	$9.2 \pm 1.0$ $9 \pm 1$	[6] [6] [8, 23]
<sup>4</sup> He	0-	0	14.6 M1 21.0 e <sup>+</sup> e <sup>-</sup>	(11.1 ± 5.4) × 10	$74 \pm 30$	$32 \pm 12$	$8 \pm 2$	[15, 5]

**Table 1.** Experimental results for anomalous e<sup>+</sup>e<sup>-</sup>-emission interpreted in the light of a short-lived 9 MeV/ $c^2$  X-boson in six M1 transitions and an M0 transition. Listed are the nucleus, the energy and the width of the resonance  $E_R$  and  $\Gamma_R$ , the (iso)spin-parity quantum numbers, the transition energy  $E_{\gamma}$ , the X-branching ratio  $B_X$  with respect to  $\gamma$ -emission, the X-decay width  $\Gamma_X$ , the coupling strength  $\alpha_X$  relative to  $\tilde{\alpha} = 1.7 \times 10^{-6}$  (the axion–nucleon coupling strength), the invariant mass  $m_X$ , and the references. Values for B<sub>X</sub> and  $m_X$  have been derived at 95% CL.

<sup>A</sup> Z	$E_R$ (MeV)	$\Gamma_R$ (eV)	$I^{\pi}, T$	$E_{\gamma}$ (MeV)	$B_X$	$\Gamma_X$ (meV)	$\frac{\alpha_X}{1.7 \times 10^{-6}}$	$m_X$ (MeV/ $c^2$ )	Refs
<sup>12</sup> C	12.71	18.1	1+,0	12.71	$(7\pm3)\times10^{-4}$	$0.24 \pm 0.11$	$18 \pm 7$	$9.0 \pm 1.0$	Present
				12.71	$(1.6 \pm 0.7) \times 10^{-3}$	$0.56\pm0.25$	$38 \pm 17$	$9.2\pm1.0$	[5–7]
	15.11	43.6	1+, 1	15.11	$\leq 4.6 \times 10^{-5}$	≤1.8	≤0.9	_	[5–7]
<sup>8</sup> Be	17.64	$10.7 \times 10^{3}$	1+, 1	17.64	$(1.1 \pm 0.3) \times 10^{-4}$	$1.9 \pm 0.4$	$1.5 \pm 0.4$	$9 \pm 1$	[2-4]
				14.64	$(8.5 \pm 2.6) \times 10^{-5}$	$0.7 \pm 0.2$	$1.5 \pm 0.4$	$9 \pm 1$	[2-4]
	18.15	$138 \times 10^3$	$1^+, 0$	18.15	$\leq 4.1 \times 10^{-4}$	≼1.2	≤5.7	_	Present
				15.15	$(5.8 \pm 2.2) \times 10^{-4}$	$2.2 \pm 0.8$	$10.5\pm4.5$	$9.5\pm1.2$	Present
<sup>4</sup> He	21.0	$850 \times 10^3$	0-,0	<b>M</b> 0	$0^- \rightarrow 0^+, e^+e^-$	$74 \pm 30$	$32 \pm 12$	$8 \pm 2$	[5–7]

## Is alpha-clustering hiding behind the scene?

											-	_				
z											19Ne	20Ne	21Ne	22Ne	23Ne	24Ne
		15F	16F	17F	18F	19F	20F	21F	22F	23F						
8								140	150	160	170	180	190	200	210	220
	10N						12N	13N	14N	15N	16N	17N	18N	19N	20N	21N
6				8C	90	10C	11C	12C	13C	14C	15C	16C	17C	18C	19C	20C
			6B	7B	8B	9B	10B	11B	12B	13B	14B	15B	16B	17B	18B	19B
4			5Be	6Be	7Be	8Be	9Be	10Be	11Be	12Be	13Be	14Be	15Be	16Be		
		3Li	4Li	5Li	6Li	7Li	8Li	9Li	10Li	11Li	12Li	13Li				
2			3He	4He	5He	6He	7He	8He	9He	10He						
		0		2		4		6		8	1	10		12		N



## An experimental challenge!

γ\* <sup>(</sup>) <sup>()</sup>) <sup>()</sup> <sup>()</sup>) <sup>()</sup> <sup>()</sup>) <sup>()</sup>

Emission of e<sup>+</sup>e<sup>-</sup> pairs coupled to the Nuclear Field. It must be disentangled from pair production due to high energy gamma rays.

- Possible only for  $\Delta E$ >1.022 MeV
- Competes with gamma emission (typical cross section ratio is 10<sup>-3</sup>)
- Allowed for monopole transitions
- <u>Allows to directly probe transition properties</u>

Theory is well established since Rose's work:

- M.E. Rose, <u>Phys Rev 76, 678 (1949);</u>
- E.K. Warburton, <u>Phys Rev 133, 6B (1964)</u>
- P. Schlüter et al, <u>Phys Rep 75, 327 (1981)</u>
- P. Schlüter et al, <u>At Data and Nucl Data Tab 24, 509 (1979)</u>

## It is possible to compute:

Pair Conversion Coefficients (PCC) Electron-positron angular correlations

Detecting "high energy" e<sup>+</sup>e<sup>-</sup> pairs (sharing 10-20 MeV of kinetic energy) emitted in an environment dominated by gamma-rays poses an experimental challenge.



## Setup: state of the art.



**Figure 1.** Comparison between the old and new setups. The previous setup (a) used 5 telescopes, each with a MWPC to gather the position of the particles and a thin scintillator in front of the main one to differentiate electrons and positrons from gammas. The new setup (b) consisted of 6 telescopes, and the MWPCs was replaced by DSSDs, which can be used for the particle identification, removing the need for the thin scintillators.



**Figure 2.** Energy sum spectrum (a) and angular correlation (b) of the  $e^+e^-$  pairs from the 17.6 MeV transition. Full blue curve shows the simulated results, and red points with error bars shows the experimental results





[D. S. Firak et al, EPJ Web of Conferences 232, 04005 (2020)]

- [J. Gulyás et al, Nucl Instr and Meth in Phys Res A 808, 21 (2016)]
- [A. J. Krasznahorkay et al, arXiv:1504.01527]

Can we provide independent data?

## We do have a useful facility





AN2000 by High Voltage Engineering Operational since 1971.

lons:  ${}^{1}({}^{2})$ H+,  ${}^{3-4}$ He+. Maximum Terminal Voltage: 2.5 MV, single stage (belt). Beam current: up to 1  $\mu$ A.





- Positrons are not discriminated from electrons. -> Future coupling to magnetic field.
- Target composition and stability are critical.
- Solid angle coverage is limited to theta=90°.
- Can we improve energy resolution?
- Angular resolution is limited by straggling:



Spessore [mm]	Energie $[MeV]$					
-F []	10	15	20			
0.7	8°	$5.5^{\circ}$	$3.5^{\circ}$			
1	$9^{\circ}$	$6.8^{\circ}$	$4.5^{\circ}$			
1.5	$11^{\circ}$	8°	$5.5^{\circ}$			

[R. Bolzonella, Preparazione di un esperimento per la misura di coppie e+e- nel decadimento del 8Be\*, Università di Padova (2019)]







Figure 3.1: Absorption position of electrons (a, b) and positrons (c, d), with a logarithmic scale on the counts, at different emission energies: 10 MeV (blue), 15 MeV (red), 20 MeV (brown).

## A new setup: proposal

- Improve angular resolution by reducing material budget.
- Improve angular coverage and measure out-of-plane correlations
- Improve confidence on target composition.
- Allow future coupling with a magnetic field.
- Focus on <sup>8</sup>Be and, possibly, <sup>12</sup>C cases.





## Design of the new setup: background suppression

- [R. Bolzonella, An experimental setup for detection of e+e pairs in the decay of <sup>8</sup>Be, Università di Padova (2021)]
- Dominant **background source: γ-rays emission** from the populated resonances
- Request to select an event:
  - coincidence in the 3 layers 0
  - most of the  $\Delta E$  is concentrated in a single bar or in the closest one 0
  - energy cuts in the  $\Delta E\text{-}E$  spectrum 0
  - $\gamma$  detection efficiency in a single clover:  $\varepsilon = 6 \cdot 10^{-4}$ 0
  - Detecting pairs: 0

$$R = \frac{N_{e^+e^-}}{N_{\gamma\gamma}} = \frac{\epsilon_l^2}{\epsilon_{\gamma}^2} \cdot \beta \qquad \longrightarrow \qquad R \sim 10$$

#### $\Delta$ E-E correlation





1 block – GEANT4 simulation



One possible configuration

14 16 Deposited energy [MeV]

- Three tests: e<sup>+</sup> and e<sup>-</sup> emitted
  - orthogonally at the center of the frontal face of a telescope
  - orthogonally at the center of the frontal face of a clover
  - isotropically in the solid angle covering a clover
- Results
  - **Deposited energy**: sum of the energies deposited in each layer of a clover



positron



- Three tests: e<sup>+</sup> and e<sup>-</sup> emitted
  - orthogonally at the center of the frontal face of a telescope
  - orthogonally at the center of the frontal face of a clover
  - isotropically in the solid angle covering a clover
- Results
  - **Deposited energy**: sum of the energies deposited in each layer of a clover
  - Measured energy: convolution of the deposited energy with a poissonian distribution depending on the light yield (30 ph/MeV, 60 ph/MeV, 100 ph/MeV)



2

#### electron

8

Positron emission energy [MeV]

10

- Three tests: e<sup>+</sup> and e<sup>-</sup> emitted
  - orthogonally at the center of the frontal face of a telescope
  - orthogonally at the center of the frontal face of a clover
  - isotropically in the solid angle covering a clover
- Results
  - **Deposited energy**: sum of the energies deposited in each layer of a clover
  - Measured energy: convolution of the deposited energy with a poissonian distribution depending on the light yield (30 ph/MeV, 60 ph/MeV, 100 ph/MeV)
  - **Efficiency distribution**: peak integral within 3σ



positron



#### electron

- **Three tests**: e<sup>+</sup> and e<sup>-</sup> emitted
  - orthogonally at the center of the frontal face of a telescope
  - orthogonally at the center of the frontal face of a clover
  - isotropically in the solid angle covering a clover
- Results
  - **Deposited energy**: sum of the energies deposited in each layer of a clover
  - Measured energy: convolution of the deposited energy with a poissonian distribution depending on the light yield (30 ph/MeV, 60 ph/MeV, 100 ph/MeV)
  - **Efficiency distribution**: peak integral within 3σ
  - Resolution distribution



positron



#### electron

- Three tests: e<sup>+</sup> and e<sup>-</sup> emitted
  - orthogonally at the center of the frontal face of a telescope
  - orthogonally at the center of the frontal face of a clover
  - isotropically in the solid angle covering a clover
- Results
  - **Deposited energy**: sum of the energies deposited in each layer of a clover
  - Measured energy: convolution of the deposited energy with a poissonian distribution depending on the light yield (30 ph/MeV, 60 ph/MeV, 100 ph/MeV)
  - Efficiency distribution: peak integral within 3σ
  - Resolution distribution
  - Distribution of the difference between the measured and the emission energy







#### electron

## Pair detection efficiency: two angular configurations

A – Angles: 0° - 60° - 120° - 180° - 270° (Atomki configuration)





B – Angles: 0° - 45° - 105° - 155° - 245°







Good compatibility in shape with respect to the Atomki configuration. [J. Gulyás et al, NIM A 808, 21 (2016)]

Estimated Pairs detection efficiency  $\varepsilon_{pairs} = 1.18 \%$ 





## Calorimeter characterization: light yield estimate using Compton scattering

EJ200 organic calorimeter

#### Setup:

- Source: <sup>60</sup>Co
- EJ200 detector read with SiPM FBK
- Ancillary detector: NaI(TI) read with PMT
- Three light readout modes:
  - 1 SiPM (6x6 mm) -> 36 mm<sup>2</sup>
  - 2 SiPMs (6x6 mm) -> 72 mm<sup>2</sup>
  - 1 SiPM (10x10) -> 100 mm<sup>2</sup>





## Calorimeter characterization: light yield estimate using Compton scattering

- Slice of the spectrum at fixed energy in the ancillary detector
- Energy in the organic scintillator fixed for energy conservation
- Projecting the slice in the organic scintillator energy measured,
  pseudo-photopeaks are produced
- Repeating the analysis for several energies, a linear trend in the plot of 1/R<sup>2</sup> against the energy is expected
- Best case: (100mm2)  $L_v = 237 \pm 5$  photons/MeV

SIPM Surface	Light Yield ph/MeV
36 mm <sup>2</sup>	35.5 ± 0.7
72 mm <sup>2</sup>	120 ± 3
100 mm <sup>2</sup>	237 ± 5





- Invariant mass depends on:
  - $\circ$  e<sup>-</sup> and e<sup>+</sup> energy
  - correlation angle
- The associated error depends on:
  - $e^-$  energy (the  $e^+$  one is fixed by the energy conservation)
  - energy resolution (depending on the light yield)
  - correlation angle
  - angular resolution
- Resolution computed as function of:  $E^-$ , Ly,  $\theta$ ,  $\sigma_{\theta}$
- Electron energy and correlation angle integrated out

Invariant mass resolution



## Tracking layer's characterization

## **Experimental setup**

- Bars read with an array of 10 SiPMs
- Signal of each SiPM distributed at the two extremes of the array using LG technology by FBK.
  - Total energy:  $E_{TOT} = E_L + E_R$
  - Energy asymmetry: *y* =



25

20

15

10

0.6 0.8 (E\_r - E\_l)/(E\_r + E\_l)



 $E_R - E_L$ 

 $E_R + E_L$ 



AN2000:

- Proton energy 200 2000 keV
- Beam current up to 1  $\mu\text{A}$
- One dedicated beamline





Protophobic vector boson:  $\Gamma(^{4}\text{He}(20.21) \rightarrow {}^{4}\text{He}X) = (0.3 - 3.6) \times 10^{-5} \text{ eV}$  (126) ATOMKI Experiment [26, 27]:  $\Gamma(^{4}\text{He}(20.21) \rightarrow {}^{4}\text{He}X) = (2.8 - 5.2) \times 10^{-5} \text{ eV}.$  (127)

The reported  $7\sigma$  anomalies reported in <sup>8</sup>Be and <sup>4</sup>He nuclear decays are both kinematically and dynamically consistent with the production of a 17 MeV protophobic gauge boson.

What is the path forward? Clearly, now is the time for other collaborations to perform the same nuclear measurements to check the ATOMKI results. But in this work, we also propose simple modifications of the ATOMKI setup that could provide incisive tests of the new particle interpretation. The comparison between theory and experiment will be sharpened considerably by including the E1 background in the experimental analysis and running on the <sup>4</sup>He(20.21) 0<sup>+</sup> resonance. In addition, scanning through the <sup>4</sup>He(20.21) 0<sup>+</sup> resonance can provide important information to disentangle vector and axial vector X bosons and quantify the properties of particles with mixed couplings. Last, we find that the protophobic vector boson could also be observable in the decays of the <sup>12</sup>C(17.23) 1<sup>-</sup> excited state, and we have provided precise predictions for this rate.

TABLE I. Production and decay kinematic parameters. Beams of protons with kinetic energy  $E_{\text{beam}}$  collide with nuclei *A* at rest to form excited nuclei  $N_*$ , which then decay to the ground state nucleus  $N_0$  through  $N_* \rightarrow N_0 X$ . We fix  $m_X = 17$  MeV, and for each of the relevant processes, we give the values of  $E_{\text{beam}}$ ,  $m_A$ ,  $m_{N_*}$ ,  $v_{N_*}$  (the  $N_*$  velocity in the lab frame),  $v_X$  (the X velocity in the  $N_*$  rest frame), and  $\theta_{e^+e^-}^{\min}$  (the minimum  $e^+e^-$  opening angle). <sup>4</sup>He(20.49) indicates the resonance energy probed in Ref. [33], which sits between the <sup>4</sup>He(21.01) and <sup>4</sup>He(20.21) states.

$p + A \rightarrow$	$N_*$	$E_{\text{beam}}$ [MeV]	$m_A$ [MeV]	$m_{N_*}$ [MeV]	$v_{N_*}/c$	$v_X/c$	$\theta_{e^+e^-}^{\min}$
$p + {}^{7}\text{Li} \rightarrow$	<sup>8</sup> Be(18.15)	1.03	6533.83	7473.01	0.0059	0.350	139°
$p + {}^{7}\text{Li} \rightarrow$	<sup>8</sup> Be(17.64)	0.45	6533.83	7472.50	0.0039	0.267	149°
$p + {}^{11}\mathrm{B} \rightarrow$	$^{12}C(17.23)$	1.40	10252.54	11192.09	0.0046	0.163	161°
$p + {}^{3}\mathrm{H} \rightarrow$	$^{4}$ He(21.01)	1.59	2808.92	3748.39	0.0146	0.587	108°
$p + {}^{3}\mathrm{H} \rightarrow$	$^{4}\text{He}(20.49)$	0.90	2808.92	3747.87	0.0110	0.557	112°
$p + {}^{3}\mathrm{H} \rightarrow$	<sup>4</sup> He(20.21)	0.52	2808.92	3747.59	0.0084	0.540	115°

# Outlook: inverse kinematics and tracking. Nuclear decay tagging.







## Outlook: inverse kinematics and tracking. Nuclear decay tagging.







[https://web.infn.it/spes/]



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## Other groups with complementary expertise are involved:

- -INFN and University of Padova
- -INFN Genova
- -INFN LNF
- -INFN Roma 1
- -INFN Roma 3
- -INFN Catania