Internal pair creation anomalies and the X-boson

T. Marchi, 31/05/2021
Outline

• Internal pair creation in Nuclear decays.
• The Hungarian anomaly: experimental evidence and interpretations.
• Direct channels and complementary approaches.
• Aipac8Be: a new setup at LNL for an independent measurement.
In a typical nuclear spectroscopy experiment:

Figure 1.21: Experimental $^{74}$Ni level scheme. On the left: the $\gamma$-ray spectrum as measured from the $^{74}$Co $\beta$ decay. On the right: level scheme as reconstructed from the systematics of even-even Ni isotopes. Adapted from [65]

**Gamma-ray emission**

<table>
<thead>
<tr>
<th>$\Delta I$</th>
<th>transition name</th>
<th>$\pi,\pi_f = +1$</th>
<th>$\pi,\pi_f = -1$</th>
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<tbody>
<tr>
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<td>monopole</td>
<td>forbidden</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>dipole</td>
<td>M1</td>
<td>E1</td>
</tr>
<tr>
<td>2</td>
<td>quadrupole</td>
<td>E2</td>
<td>M2</td>
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<tr>
<td>3</td>
<td>octupole</td>
<td>M3</td>
<td>E3</td>
</tr>
</tbody>
</table>

Table 2.1: Electromagnetic transitions involving photon emission allowed by the selection rules. The list is limited to $\Delta I \leq 3$. 

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**Foreword: Nuclear Transitions and Internal Pair Creation**

In a typical nuclear spectroscopy experiment:
Emission of $e^+e^-$ 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 $10^{-3}$)
- Allowed for monopole transitions
- Allows to directly probe transition properties

Theory is well established since Rose’s work:
- M.E. Rose, Phys Rev 76, 678 (1949);
- E.K. Warburton, Phys Rev 133, 6B (1964)
- P. Schlüter et al, At Data and Nucl Data Tab 24, 509 (1979)

It is possible to compute:
- Pair Conversion Coefficients (PCC)
- Electron-positron angular correlations

Detecting “high energy” $e^+e^-$ pairs (sharing 10-20 MeV of kinetic energy) emitted in an environment dominated by gamma-rays poses an experimental challenge.
The $^{19}\text{F}(p,\alpha)^{16}\text{O}^*$ reaction is the calibration standard for $e^+e^-$ correlations since 1950’s.
Beam energies: 0.5 – 1.5 MeV.
Transition of interest ($E_0$): $^{16}\text{O}(6.06 \text{ MeV}; 0^+) \rightarrow \text{g.s.}$

Computed using Rose’s model

[J. Gulyás et al, Nucl Instr and Meth in Phys Res A 808, 21 (2016)]
The reaction: $^7\text{Li}(p,e^+e^-)^8\text{Be}$ 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.
The Hungarian setup for pair spectrosocopy.

\[ \Delta \theta \sim 2^\circ, \text{ but:} \]

The simulated angular resolution corresponds to FWHM \( \approx 7^\circ \).
We use bins of 10° in the correlation spectra.

[J. Gulyás et al, Nucl Instr and Meth in Phys Res A 808, 21 (2016)]
The Hungarian setup.

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[J. Gulyás et al, Nucl Instr and Meth in Phys Res A 808, 21 (2016)]
The updated Hungarian setup.

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)]
The Hungarian anomaly

Krasznahorkay et al. (2016)
Beam: protons in the 0.5 - 1.2 MeV range
Targets: LiF$_2$, LiO$_2$. 

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The deviation between the experimental and theoretical angular correlations is significant and can be described by assuming the creation and subsequent decay of a \( J^P = 1^+ \) boson with \( m_0 c^2 = 16.70 \pm 0.35 \text{(stat)} \pm 0.5 \text{(syst)} \) 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 \(^8\)Be was found to be \( 5.8 \times 10^{-6} \) 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 (Z\(_d\)) suggested for explaining the muon anomalous magnetic moment [7].
Zhang and Miller extend Rose’s theory:

- Halo-Effective field theory framework considering polarization.
- Naturally includes different multipoles interference.
- Includes constraints on pair productions coming from gamma-ray spectroscopy.
- Ad-hoc form factors are considered.

The improvements can not explain the anomaly.

Here we focus on the vector case. We consider a massive spin-1 Abelian gauge boson $X$ that couples nonchirally to standard model (SM) fermions with charges $e_f$ in units of $e$. The new Lagrangian terms are

$$\mathcal{L} = -\frac{1}{4} X_{\mu} X^{\mu} + \frac{1}{2} m_X^2 X_{\mu} X^{\mu} - X^{\mu} J_{\mu},$$  \hspace{1cm} (1)$$

Coupling's constraints:

$$\frac{\Gamma(^{8}\text{Be}^* \rightarrow ^{8}\text{Be} X)}{\Gamma(^{8}\text{Be}^* \rightarrow ^{8}\text{Be} \gamma)} = (\varepsilon_\mu + \varepsilon_\nu)^2 \frac{|\mathbf{p}_X|^2}{|\mathbf{p}_\gamma|^2} \approx 5.8 \times 10^{-6},$$  \hspace{1cm} (4)$$

which implies

$$|\varepsilon_\mu + \varepsilon_\nu| \approx 3.7 \times 10^{-3}. \hspace{1cm} (5)$$

Therefore, the strength of the Atomki signal provides a constraint only on the sum of the $X$ couplings to the up and down quarks, and does not depend on the couplings to leptons.

The theory introduces a new vector boson: the X17 particle.
The Hungarian anomaly, updated

Further data with improved setup

A.J. Krasznahorkay et al, EPJ Web of Conferences 137, 08010 (2017)
A.J. Krasznahorkay et al, EPJ Web of Conferences 142, 01019 (2017)
D. S. Firak et al, EPJ Web of Conferences 232, 04005 (2020)

A different reaction
No evidence in the available data, new setup proposed.
The Mysterious X Boson Could Upend the Standard Model. If It Actually Exists

CERN COURIER
SEARCHES FOR NEW PHYSICS | NEWS
Rekindled Atomki anomaly merits closer scrutiny
20 December 2019

NATIONAL PHYSICS
Evidence of a 'Fifth Force' Faces Scrutiny
By NATALIE WOLCHOVER
June 7, 2018

A lab in Hungary has reported an anomaly that could lead to a physics revolution. But even as excitement builds, closer scrutiny has unearthed a troubling backstory.

This Is Why The 'X17' Particle And A New, Fifth Force Probably Don't Exist

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group ©
Science
The Universe is out there, waiting for you to discover it.
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 $^4\text{He}(20.21)$ 0$^+$ resonance. In addition, scanning through the $^4\text{He}(20.21)$ 0$^+$ 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 $^{12}\text{C}(17.23)$ 1$^-$ 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 $\theta_{e^+ e^-}^{\text{min}}$ (the minimum $e^+ e^-$ opening angle). $^4\text{He}(20.49)$ indicates the resonance energy probed in Ref. [33], which sits between the $^4\text{He}(21.01)$ and $^4\text{He}(20.21)$ states.

<table>
<thead>
<tr>
<th>$p + A \rightarrow$</th>
<th>$N_*$</th>
<th>$E_{\text{beam}}$ [MeV]</th>
<th>$m_A$ [MeV]</th>
<th>$m_{N_*}$ [MeV]</th>
<th>$v_{N_*}/c$</th>
<th>$v_X/c$</th>
<th>$\theta_{e^+ e^-}^{\text{min}}$</th>
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<tr>
<td>$p + ^7\text{Li} \rightarrow$</td>
<td>$^8\text{Be}(18.15)$</td>
<td>1.03</td>
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<td>7473.01</td>
<td>0.0059</td>
<td>0.350</td>
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Is alpha-clustering hiding behind the scene?

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<td>10H</td>
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![Diagram showing isotopes and their properties]

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The diagram illustrates the distribution of isotopes, highlighting the-alpha clustering phenomenon, which suggests that certain isotopes may be more stable or common than others in a given element's atomic number range.
Let’s have a look back in time

Results of two dedicated experiments are reported yielding further indications for an anomaly at 9 MeV/c² in the angular correlation of IPC. The first experiment (8Be) shows a deviation from IPC at 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.

A “pandemonium” of X-bosons
The ATOMKI group has been studying e+e- pairs for decades

LEPTON PAIRS FROM A FORBIDDEN M0 TRANSITION: SIGNALING AN ELUSIVE LIGHT NEUTRAL BOSON?

A. Krasznahorkay a, F.W.N. de Boer b, M. Csatlós a, L. Csige a, Z. Gács a, J. Gulyás b, M. Hunyadi a, T.J. Ketel b, J. van Klinken d, A. Krasznahorkay Jr. a, A. Vitéz c

4. Conclusion

We observed for the first time the 10.95 MeV 0⁺ → 0⁺ decay in 16O by measuring e⁺e⁻ pairs. The energy sum of the pairs corresponds to the energy of the transition (10.95 MeV), and the branching ratio B = (20 ± 5) × 10⁻⁵ agrees with that of the expected boson. The angular correlation of the pairs might be described by assuming the decay of a boson with a mass of m = 9–10 MeV/c². New experiments with better statistics are needed to settle the question and to determine the mass of the boson more precisely.
Recent theoretical efforts by Italian groups.

The chiral-effective-field-theory (χEFT) framework is used to describe nuclear dynamics and to model the interactions of nucleons with the hypothetical boson.

Ab initio calculations for the differential cross sections of the $^3$H(p, e$^+$e$^-$) $^4$He and $^3$He(n, e$^+$e$^-$) $^4$He reactions.
Two open questions:

1. Experimental confirmation of the anomaly
2. Contradicting interpretations

call for new experimental efforts
Heavy-ion accelerator complex

T.A.P.

SPES

CN

AN2000
AN2000:
- Proton energy 200 – 2000 keV
- Beam current up to 1 μA
- One dedicated beamline
A new setup: criticalities and solutions

- Positrons are not discriminated from electrons.
- Target composition and stability are critical.
- Solid angle coverage is limited to theta=90°.
- Angular resolution is limited by straggling:

<table>
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<tr>
<th>Spessore [mm]</th>
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<tr>
<td>1</td>
<td>9°</td>
</tr>
<tr>
<td>1.5</td>
<td>11°</td>
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[R. Bolzonella, Preparazione di un esperimento per la misura di coppie e+e- nel decadimento del 8Be*, Università di Padova (2019)]
A new setup: criticalities and solutions

- 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 $^8$Be and, possibly, $^{12}$C cases.

Courtesy of A. Gambalonga - LNL
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: prototypes
Outlook: inverse kinematics and tracking. Nuclear decay tagging!

$^{11}\text{B} + \text{iC}_4\text{H}_{10}$ at 32 MeV

3 stopped particles in the output channel
• Internal pair creation is an exotic and challenging process in Nuclear Physics, typically used to study gamma-forbidden transitions (such as E0).
• Anomalies in the e+e- angular correlation distributions have been reported for specific transitions in $^{8}$Be* and $^{4}$He* excited by resonant reactions.
• Several interpretations claim the existence of a previously unknown vector boson with mass of about 17 MeV/c2, possible mediator of a new force.
• The direct observation via e+ + e- scattering is being studied but not yet reported.

• Several experimental studies are being proposed and prepared worldwide. At LNL a dedicated setup is being developed by a cross-experiment collaboration.

...stay tuned and thanks for listening!
The experimental work is funded by INFN-CSN3 through the NUCLEX collaboration.

Other groups with complementary expertise are involved:
- INFN and University of Padova
- INFN Genova
- LNF
- INFN Roma 1
- INFN Roma 3 (Antonio and Diego)
- INFN Catania