FRIB

Theory overview on X17 (SM)

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Facility for Rare Isotope Beams (FRIB)

- FRIB is a $730 million scientific user facility funded by the Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan. It is the world’s premier center for rare isotope research, supporting the Office of Nuclear Physics mission in DOE-SC.
- FRIB construction started in 2008 and completed ahead of schedule and on budget. The ribbon cutting was held in May 2022, and the first experiments began thereafter.
- Rare isotopes are atomic nuclei composed of unusual combinations of protons and neutrons and do not naturally exist on Earth. They are produced in violent astrophysical events, and FRIB can now make them.
- FRIB enables scientists to discover the properties of rare isotopes and the physics of atomic nuclei, understand the formation of elements in the Universe, test the fundamental interactions and symmetries of nature, and provide societal benefits in medicine, energy, industry, security, environment, and other applications.

Discovery Potential at FRIB

- The science of FRIB:

Discover the properties of rare isotopes and the physics of atomic nuclei. Push the science frontiers and discover new phenomena.

Provide rare isotopes for societal benefits in medicine, energy, industry, security, environment, and other applications

Model astrophysical processes, interpret astronomical data, and understand the formation of elements in the Universe

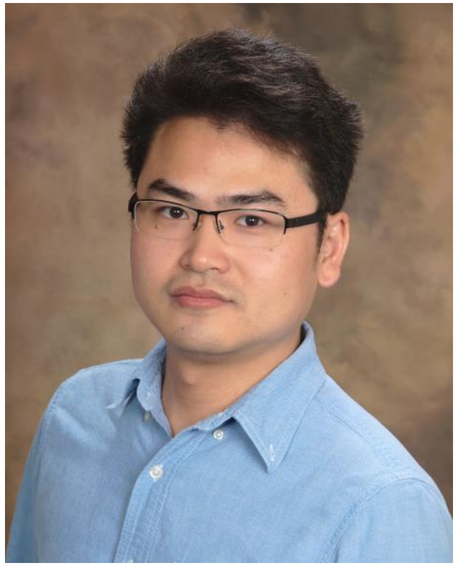
Use isotopes that provide enhanced sensitivity to test the fundamental interactions and symmetries of nature

FRIB

- FRIB addresses important questions related to fundamental science and applications of atomic nuclei

Myself

- I got my bachelor degree at USTC in 2004
- Research interests (mostly in nuclear theory):
  - Nuclear few-body and many-body systems
  - Effective field theories
  - Applications of Bayesian statistics
  - Machine learning and model reduction methods
  - Nuclear physics connected to the BSM physics search



Outline

- Brief introduction of the Atomki anomalies
- What are the nuclear theory predictions based on Standard Model (SM)?
- A nuclear theory input for Beyond-SM (BSM) studies (is X17 a protophobic vector boson?)
- Summary

Atomki anomalies

PRL **116,** 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

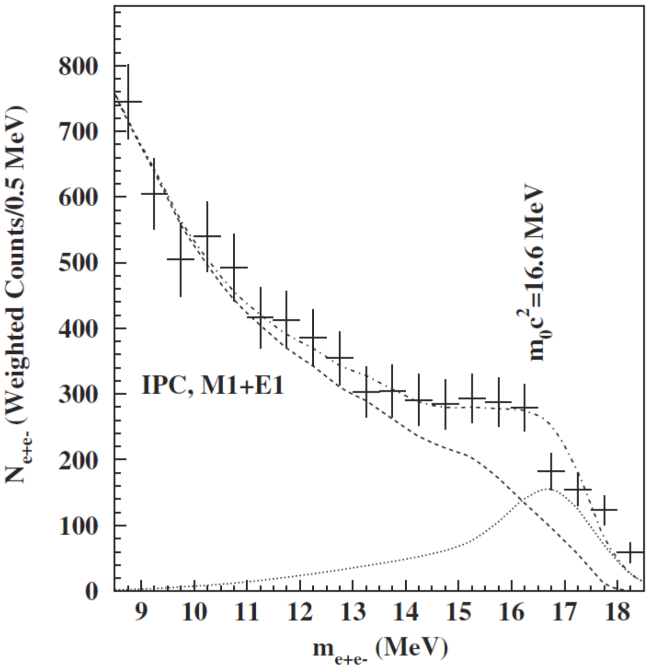
Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

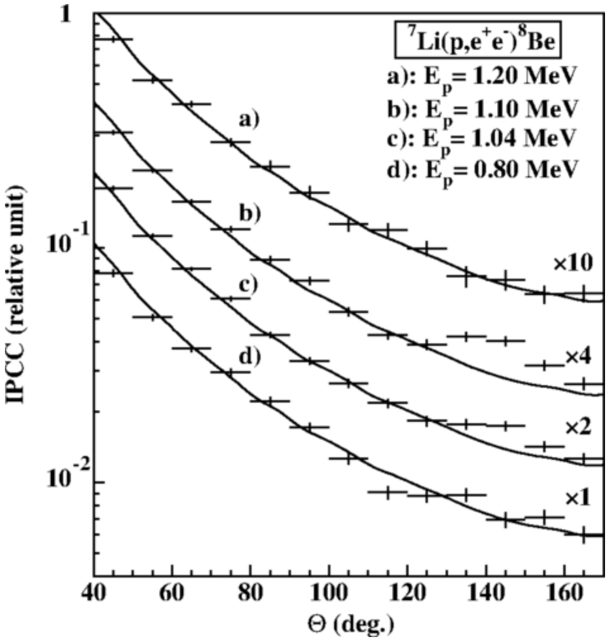
A. J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, and Zs. Vajta
Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

T. J. Ketel
Nikhef National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, Netherlands

A. Krasznahorkay
CERN, CH-1211 Geneva 23, Switzerland and Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary
(Received 7 April 2015; published 26 January 2016)

Electron-positron angular correlations were measured for the isovector magnetic dipole 17.6 MeV ($J^\pi = 1^+$, $T = 1$) state → ground state ($J^\pi = 0^+$, $T = 0$) and the isoscalar magnetic dipole 18.15 MeV ($J^\pi = 1^+$, $T = 0$) state → ground state transitions in ^{8}Be. Significant enhancement relative to the internal pair creation was observed at large angles in the angular correlation for the isoscalar transition with a confidence level of $> 5\sigma$. This observation could possibly be due to nuclear reaction interference effects or might indicate that, in an intermediate step, a neutral isoscalar particle with a mass of $16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})$ MeV$/c^2$ and $J^\pi = 1^+$ was created.



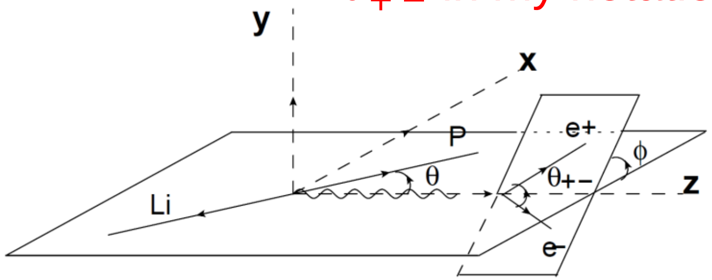


θ_{+-} in my notation

$\boldsymbol{p + {}^7Li \rightarrow {}^8Be_{gs} + e^+ + e^-}$ (PRL 116, 042501, 2015)

$\boldsymbol{p + {}^3H \rightarrow {}^4He + e^+ + e^-}$ (arXiv:1910.10459 and PRC 104, 044003, 2021)

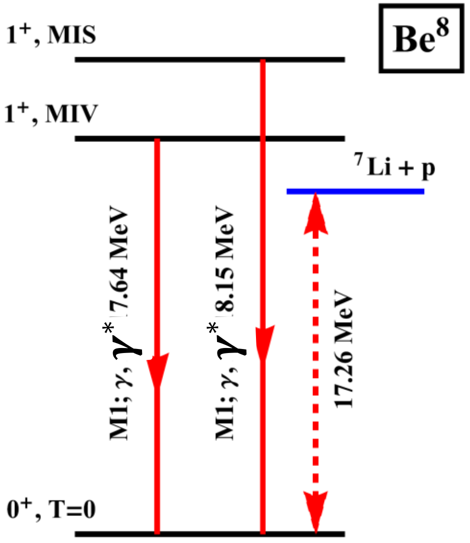
$\boldsymbol{p + {}^{11}B \rightarrow {}^{12}C + e^+ + e^-}$ (PRC 106, L061601, 2022)

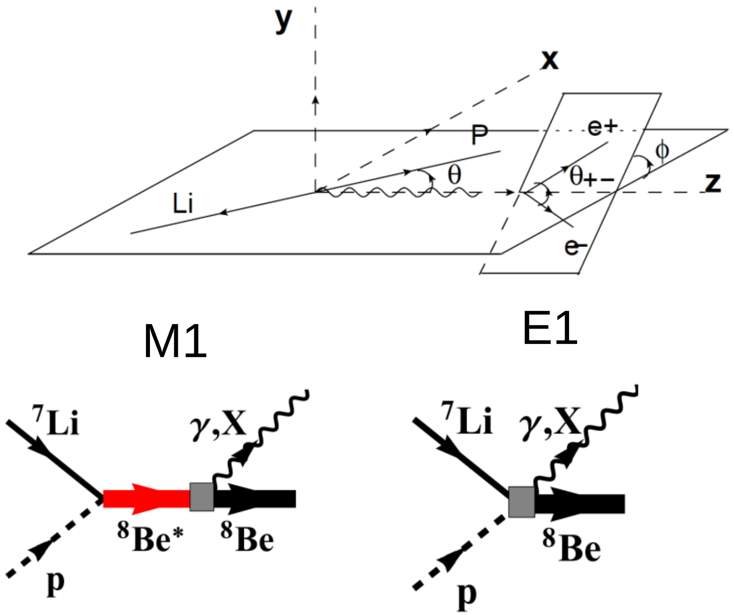


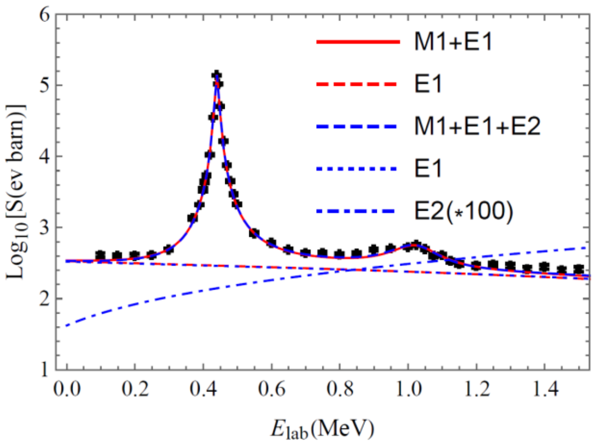
Can nuclear physics explain?

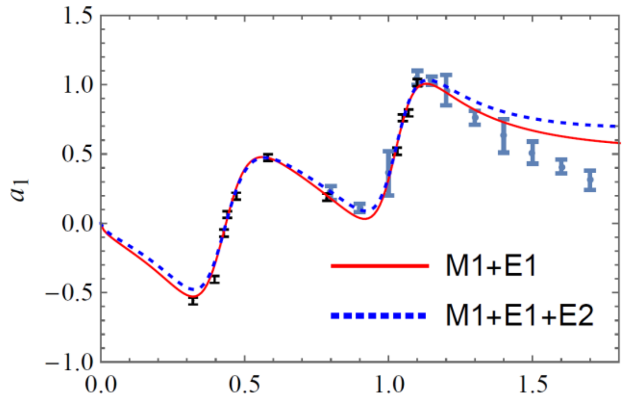
- The models used in experimental analysis: M. E. Rose [PR 76, 678 (1949)] without inferences
- Details about our model are in X.Z. and G. A. Miller, Phys.Lett.B 773 (2017) 159-165 [1703.04588]
- It is about EM multipole (E1, M1, and/or E2) interferences and potential multipole form factor
- The model was tuned to existing photon data (showing anisotropy)

$$\sum |\mathcal{M}_\gamma|^2 \equiv T_0 + T_1\, P_1(\cos\theta) + T_2\, P_2(\cos\theta)$$









- More complex θ, ϕ dependence for $e^+ - e^-$ production
- This model is used in the simulations of MEGII's search for X17

Can nuclear physics explain?

- Interference and anisotropy do NOT explain the anomaly; EM transition form factor can, but it is unphysical (requiring a large distance scale)
- Other nuclear theory studies for the Be8 system don't find SM explanations based on one-boson approximation.
- However, it is possible that the higher order correction due to two-photon exchanges might be relevant. Note the anomalous signal is very small as compared to SM background.

"*A Standard Model Explanation for the ATOMKI Anomaly*," A. Aleksejevs et al., arXiv: 2102.01127

- Nuclear theory conclusion is uncertain

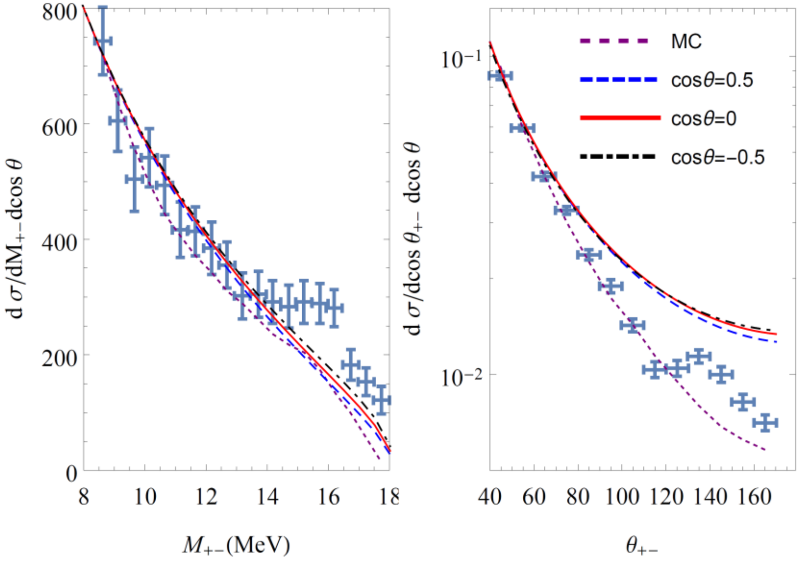


FIG. 6. The differential cross sections vs M_{+-} (left) and θ_{+-} (right) with $\cos\theta = 0$ and ± 0.5. "MC" is the experimental MC simulation [1]. In the M_{+-} distribution, the last data point [1] with M_{+-} above the so-called Q value, i.e., $E_{th} + E_{(0)} = 18.15$ MeV, is not shown here. The normalizations of our results in two plots are chosen such that the results agree with data in the lowest M_{+-} and θ_{+-} bins.

Anisotropy?

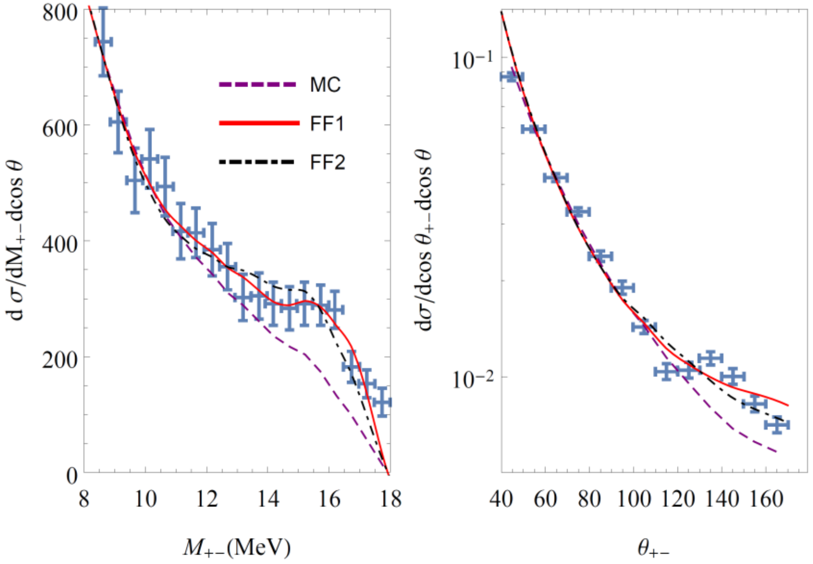


FIG. 7. The differential cross sections vs M_{+-} and θ_{+-} with $\theta = 90°$. Again "MC" is the MC simulation. The other curves are explained in the text.

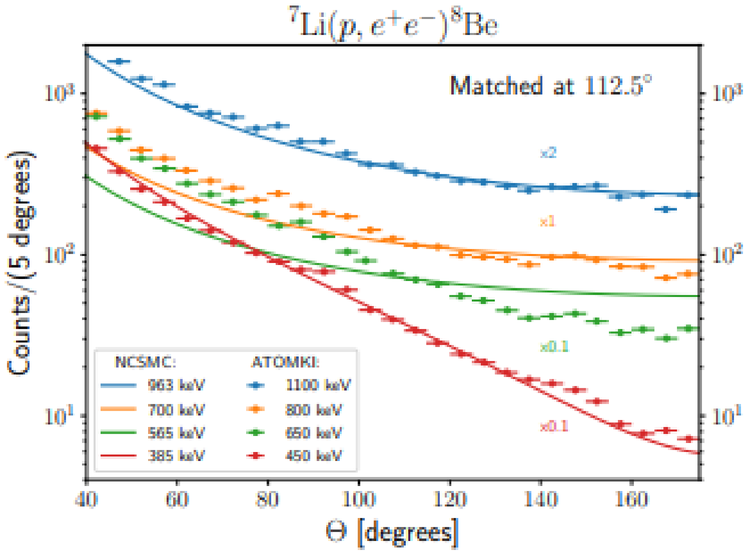
M1 form factor?

Other nuclear theory studies

$\textit{Ab initio}$ investigation of the ^{7}Li$(p, e^+e^-)^8$Be process and the X17 boson

P. Gysbers[1,2], P. Navrátil[1], K. Kravvaris[3], G. Hupin[4], S. Quaglioni[3]
[1] *TRIUMF, Vancouver, British Columbia, V6T 2A3, Canada*
[2] *Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, V6T 1Z1, Canada*
[3] *Lawrence Livermore National Laboratory, P.O. Box 808, L-414, Livermore, CA 94551, USA and*
[4] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
(Dated: August 29, 2023)

Gysbers et al, 2023 [arXiv: 2308.13751]



(a)

PHYSICAL REVIEW C **105**, 055502 (2022)

Angular correlations in the e^+e^- decay of excited states in ^{8}Be

A. C. Hayes,[1] J. Friar,[1] G. M. Hale,[1] and G. T. Garvey[1,2]
[1] *Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2] *Department of Physics, University of Washington, Seattle, Washington 98195, USA*

TRIUMF-2022 IOP Publishing
Journal of Physics: Conference Series **2391** (2022) 012009 doi:10.1088/1742-6596/2391/1/012009

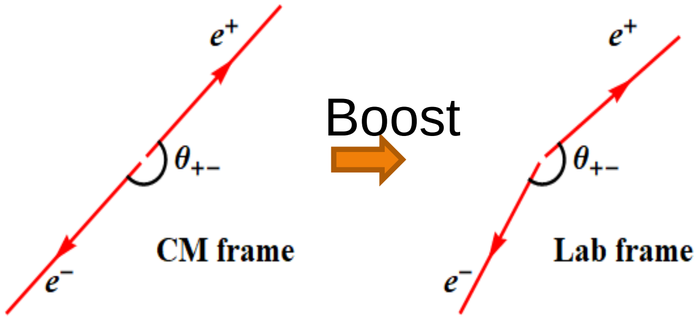
Theoretical study of the ^{3}H$(p, e^+e^-)^4$He and ^{3}He$(n, e^+e^-)^4$He processes and the X17 anomaly

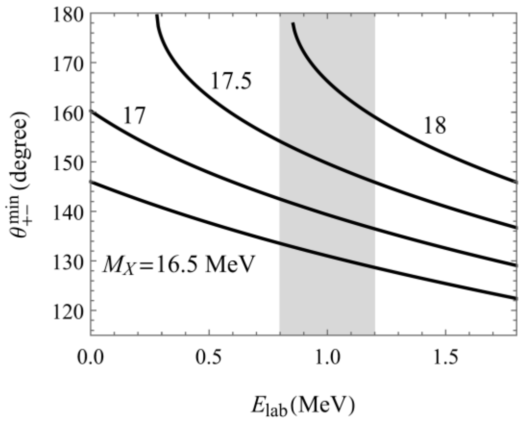
M. Viviani
[1] INFN-Pisa

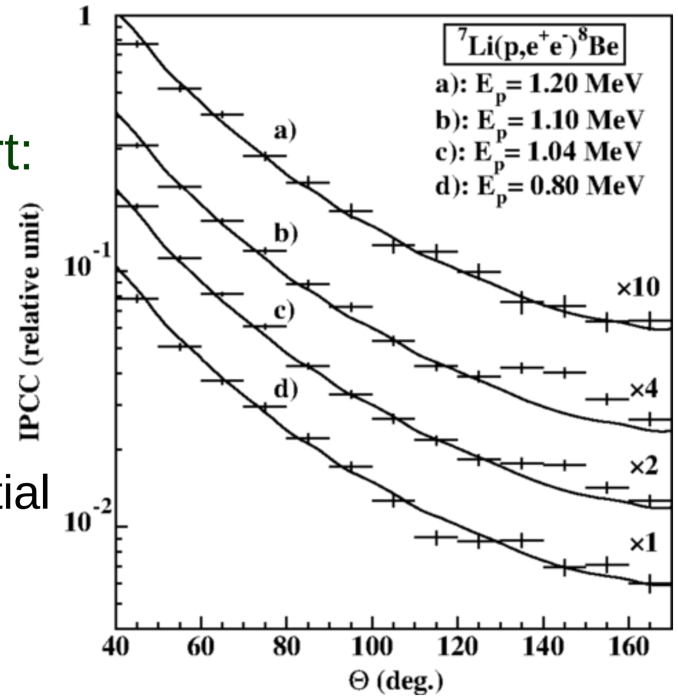
No nuclear theory explanation based on **one-photon** approximation

Can a protophobic vector boson explain?

- Details are in XZ and G. A. Miller, Phys.Lett.B 813 (2021) 136061 [2008.11288]
- This was an interesting development, which can be found in the review report: *Shedding light on X17: community report, Eur.Phys.J.C 83 (2023) 3, 230.*
  - J.L. Feng et.al., (2016, 2017): protophobic X (17 MeV) in the Be-8 transition
  - J.L. Feng et.al., (2020): consistent explanation in both Be-8 and He-4 transitions
  - Nontrivial part: the required X properties, including protophobia, couplings and masses, are consistent with existing constraints
  - Our study: such vector boson would be seen in all the energies measured in the initial Atomki measurement (2015), conflicting their measurements.







Krasznahorkay et al., 2016, the original Atomki PRL report

Can a protophobic vector boson explain?

- The X production amplitude is directly proportional to photon production
- Including differences in kinematics and polarization vectors → dominance of the energy-smooth nonresonant (Bremsstrahlung) component
- Other multipoles only increase the nonresonant component
- This is confirmed in other nuclear microscopic calculations for the Be8 system (Gysbers et al, 2023)
- This proportionality is confirmed for the He4 system in a separate study (Viviani et al, 2022)

$$J^\mu_\gamma = \overline{N}\left(\Gamma^\mu_s + \Gamma^\mu_v \tau_3\right) N$$

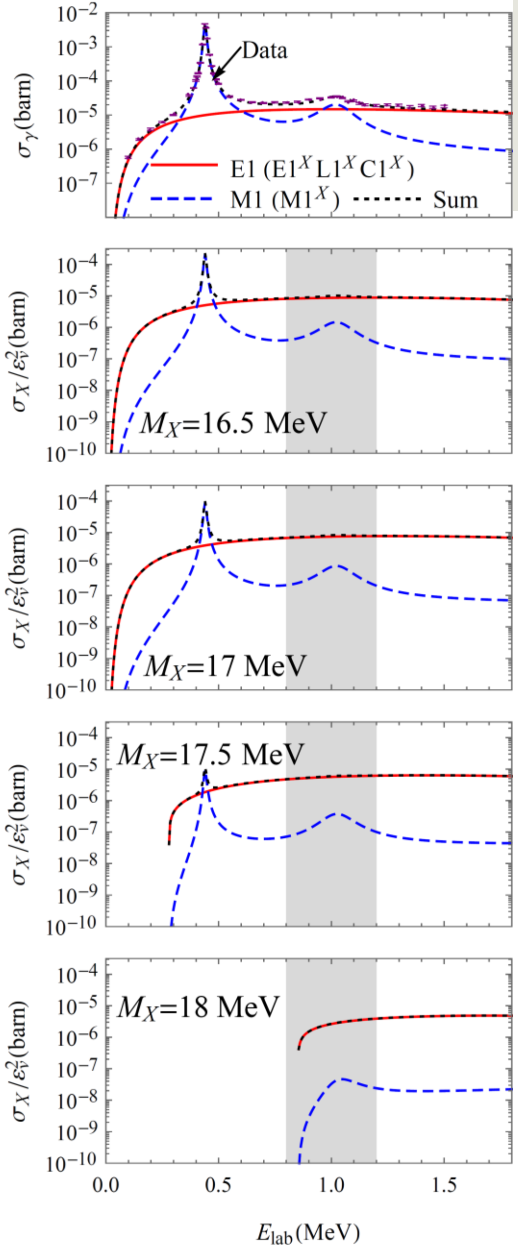
$$J^\mu_X = \overline{N}\left(\varepsilon_s \Gamma^\mu_s - \varepsilon_v \Gamma^\mu_v \tau_3\right) N$$

R. D. Lawson, Theory of the nuclear shell model (Oxford University Press,1980) :

$$\mathcal{O}^\gamma_{\mathrm{E1}} = e_{\mathrm{EM}} \sqrt{\frac{3}{4\pi}} \sum_{i=1}^{A} \boldsymbol{r}_{(i)} \frac{\tau_{(i),3}}{2}$$

$$\mathcal{O}^\gamma_{\mathrm{M1}} \overset{\text{here}}{\approx} \sqrt{\frac{3}{4\pi}} \frac{e_{\mathrm{EM}}}{2M_N} \sum_i \left[\left(\lambda^{(1)} + \frac{1}{4}\right)\boldsymbol{\sigma}_{(i)} + \frac{1}{2}\boldsymbol{J}_{(i)}\right] \tau_{(i),3}$$

$$\varepsilon_s \approx \varepsilon_v \rightarrow \quad \mathcal{O}^X_{\mathrm{E1}} = -\varepsilon_v \mathcal{O}^\gamma_{\mathrm{E1}}, \quad \mathcal{O}^X_{\mathrm{M1}} \approx -\varepsilon_v \mathcal{O}^\gamma_{\mathrm{M1}}$$



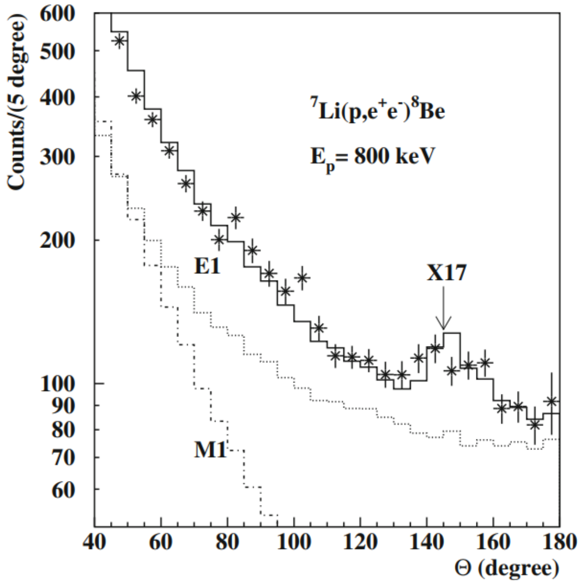
Can a protophobic vector boson explain?

- Story wasn't finished there…
- In the 2021 workshop "Shedding light on X17" held at Centro Ricerche Enrico Fermi (and online), it was presented and later detailed in the summary report (*Eur.Phys.J.C 83 (2023) 3, 230*), and then in arXiv:2205.07744 in 2022:

2.1 X17: status of the experiments on ^{8}Be and ^{4}He

Attila J. Krasznahorkay

In our very recent work [54], we report the results of the measurements of the angular correlations of the e^+e^- pairs created in the ^{7}Li(p, γ) reaction at proton energies of E_p = 450 keV, 650 keV, 800 keV and 1100 keV. As a typical example, Fig. 6 shows the angular correlation measured at E_p = 800 keV.



arXiv:2205.07744

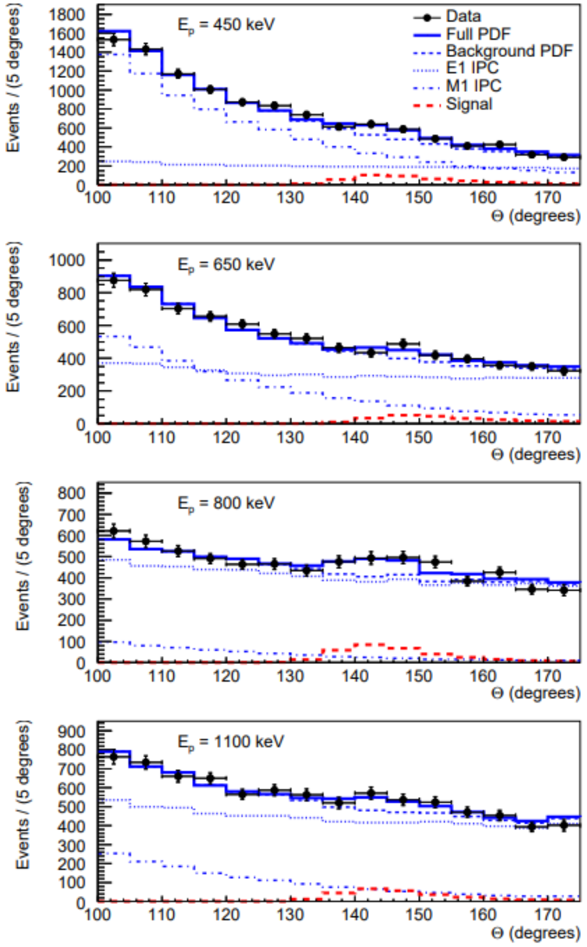
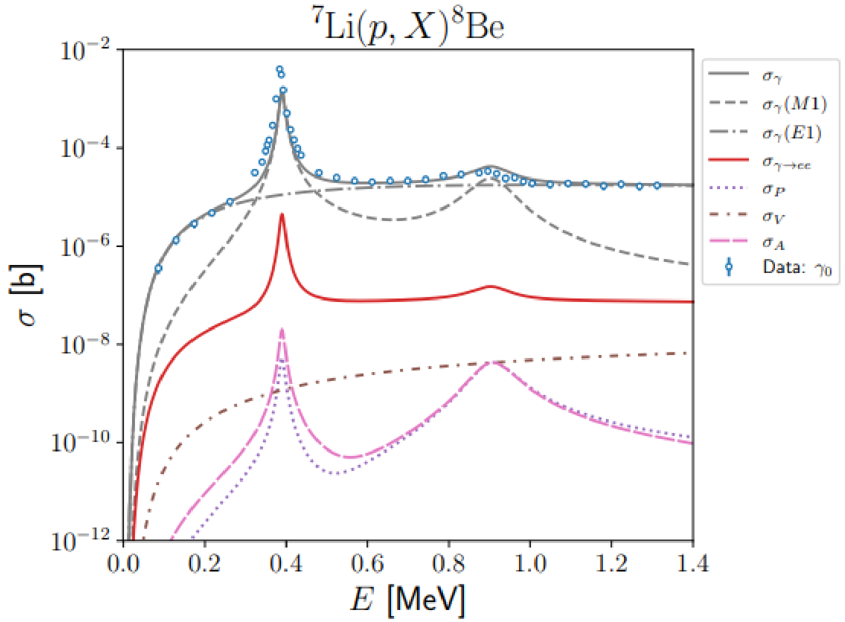


FIG. 5. See the figure caption of Fig. 4. The fit was performed for the angular region of the anomaly.

- So, the protophobic vector boson explanation is viable?

Other nuclear theory studies

Gysbers et al, 2023 [arXiv: 2308.13751]

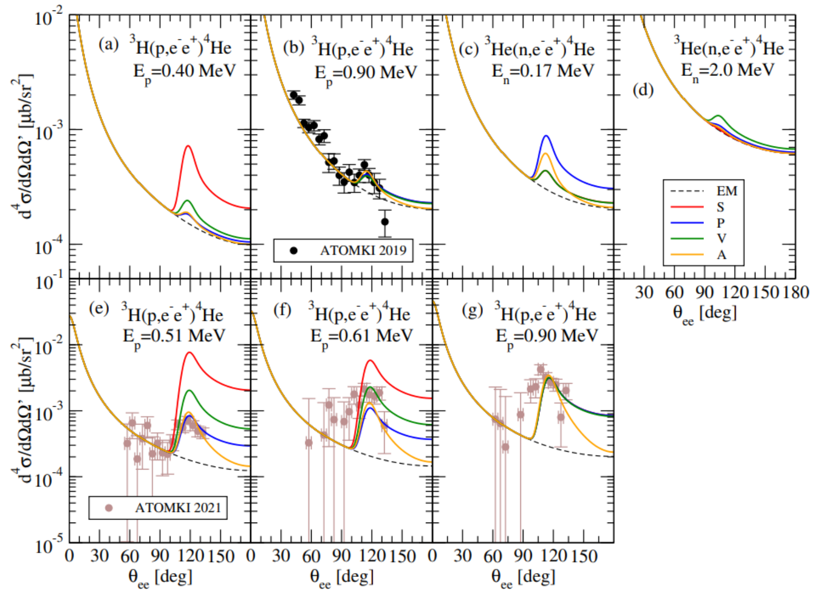


Viviani et al, 2022

PHYSICAL REVIEW C **105**, 014001 (2022)

$X17$ boson and the ^{3}H$(p, e^+e^-)^4$He and ^{3}He$(n, e^+e^-)^4$He processes: A theoretical analysis

M. Viviani,[1] E. Filandri,[2,3] L. Girlanda,[4,5] C. Gustavino,[6] A. Kievsky,[1] L. E. Marcucci,[1,7] and R. Schiavilla[8,9]



From M. Viviani, Journal of Physics: Conference Series 2391 (2022) 012009

Novel hadronic physics ideas:

arXiv:2206.14441

Quantum Chromodynamics Resolution of the ATOMKI Anomaly in ^{4}He Nuclear Transitions

Valery Kubarovsky,[1] Jennifer Rittenhouse West,[2,3] and Stanley J. Brodsky[4]

[1] *Thomas Jefferson National Accelerator Laboratory, Newport News, VA 23606, USA*
[2] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[3] *EIC Center at Thomas Jefferson National Accelerator Laboratory, Newport News, VA 23606, USA*
[4] *SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94309, USA*
(Dated: Tuesday 19th July, 2022)

Invoke EM transition form factor based on novel quark wave function in nuclear state

Summary

- Nuclear theory based on one-photon approximation can’t explain the Atomki anomalies
- Nuclear theory predictions for the pair productions are valuable for experimental simulations. These processes have nontrivial multipoles interferences & anisotropies.
- Other potentially viable nuclear theory explanations: two-photon exchange diagrams, and novel hadronic structure in nuclear states
- Nuclear theory is needed to study BSM proposals: such as the debate on X17’s protophobic vector nature, based on nuclear isospin symmetry
- More experimental approves/disapproves are needed