From Nuclear Few-Body Systems to Beyond the Standard Model:

Theoretical Studies of the X17 Boson

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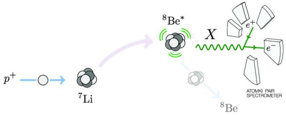
X17 Boson

A Curious Signal in Nuclear Decays



(see Attila Krasznahorkay talk)

Image from (Feng et al., (2016))

- Around 2016, the ATOMKI lab in Debrecen (Hungary) reported unexpected features in nuclear transitions
- Reactions: ^{7}Li$(p, e^+e^-)^8$Be and ^{3}H$(p, e^+e^-)^4$He(Krasznahorkay et al., PRL 116 (2016), Krasznahorkay et al.,1910.10459 (2019))
- A 6-7σ bump in the angular distribution of e^+e^- pairs suggested a possible new boson: the "X17"

Confirmations

- Same bump observed in ^{11}B$(p, e^+e^-)^{12}$C
- Hanoi (VNU University) confirmed excess in ^{8}Be transition (Koch et al., PRC 101 (2020))
- Repeated ATOMKI experiments reinforce original claim (Krasznahorkay et al., PRC 103 (2021))
- Observed excess at opening angles $\theta_{ee} \sim 140^\circ$ (^{8}Be) and 110° (^{4}He)

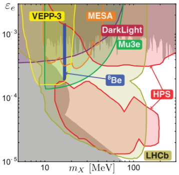
Searches for X17: Ongoing and Future Experiments

- **PADME** (LNF-INFN): search for e^+e^- resonances from positron annihilation on target (L. Darmé et al., Phys. Rev. D 106, 115036 (2022)), https://agenda.infn.it/event/46808
- **MEG II**:^{8}Be decay (A.M. Baldini et al. (MEG II), Eur. Phys. J. C 78, 380 (2018), Barducci et al, HEP 04 (2025)) (see H. Benmansour talk)
- **TREK/E36**: precision e^+e^- pair detection in kaon decays (Balewski et al., arXiv:1412.4717)
- **Montreal X17 Project**: dedicated experiment for ^{8}Be transitions (T.P.G. Azuelos)
- **n_ ToF at CERN**: $^3\text{He}(n, e^+e^-)^4\text{He}$
- **MAGIX @ MESA** (Mainz): e beam on gasous target (L. Doria et al., PoS ALPS2019, 022 (2020))
- **NA64, Belle II** (CERN, KEK): missing energy techniques for visible and invisible decays (NA64 Coll., Phys. Rev. D 97 (2018); E. Kou et al. (Belle II), PTEP 2019, 123C01 (2019))
- **New JEDI**: broad search for visible/invisible decays over large mass/coupling range (B. Bastin et al., EPJ Web Conf. 275, 01012 (2023))
- **JLab**: for nuclear transitions and e^+e^- detection (see A. Gasparian talk)

..and theoretical speculations

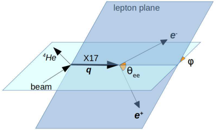
- MeV-scale bosons are suggested by dark matter portals and fifth-force models (Delle Rose, Khalil, Moretti, (2019)),(Feng, Tait, Verhaaren, (2020)), (Fayet, 2020),(Alves, 2020)$\cdots$

Constraints from Other Experiments: The "Protophobic" Hypothesis



- NA48/2: $\varepsilon < 8 \times 10^{-4}$(90% CL) (Batley et al., PLB 746 (2015))
- SLAC E141: $|\varepsilon_e| > 2 \times 10^{-4}$(E. M. Riodan et al., PRL 59 (1987)), KLOE-2: $|\varepsilon_e| < 2 \times 10^{-3}$ (A. Anastasi et al., PRL 750 (2015))
- Limits vary with X17's nature: scalar, pseudoscalar, vector, axial, etc. (Kahn et al., JHEP 05 (2017))
- To evade constraints, X17 may couple more strongly to neutrons than protons $\Rightarrow$A "protophobic" vector boson fits some anomalies (Feng et al., PRL 117 (2016))
- Implications for magnetic moments:
  - $(g-2)_\mu$: potential explanation of the discrepancy(B. Abi et al. PLB (2015)),(Borsanyi et al., (2021))
  - $(g-2)_e$: recent Rb recoil data compatible with MeV-scale vector boson(Morel et al., (2020))

Alternative Interpretations



- Higher-order QED corrections (A. Aleksejevs (2021)),(B.Koch, Nucl.Phys.A, (2021)
- Population of higher excited nuclear states(P. Kalman et al., Eur. Phys. J. A , (2020)

Both could mimic angular correlation bumps

Why Nuclear Structure Matters

- Most of the speculations based on "resonance saturation"(resonance → ground state + X17, X17→ $e^+ e^-$)
- But real nuclear processes involve multiple excited states and continuum contributions
- Accurate treatment needs realistic nuclear structure and dynamics (Viviani et al., PRC 105 (2021))

Nuclear Reactions Studied:

- $^3\mathrm{H}(p, e^+e^-)^4\mathrm{He}$
- $^3\mathrm{He}(n, e^+e^-)^4\mathrm{He}$

and:

- $\mathbf{d(p, e^+e^-)^3He}$
- $\mathbf{d(n, e^+e^-)^3H}$

Why? The system with A = 3 not presenting a structure of resonant levels provides a study very instructive and can give information on the coupling of X17 with protons and neutrons separately

Ab Initio Calculations via Chiral EFT

We need:

1. Initial/final wave functions Ψ_{E_i}, Ψ_{E_f}
2. Transition operators (currents $\hat{J}$)

$$\sigma(E) \propto \int \sum dE_f \langle \Psi_{E_i} | \hat{J} | \Psi_{E_f} \rangle \left\langle \Psi_{E_f} | \hat{J} | \Psi_{E_i} \right\rangle \delta \left(E_f - E \right)$$

$\Downarrow$

$R(E) =$ Response function

(see F. Bonaiti and A. Gnech talks)

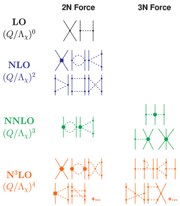
Ab Initio Calculations via Chiral EFT(II)

- Bound- and scattering-state wave functions obtained via Hyperspherical Harmonics (HH) method:
  - $$\Psi = \sum_{\mu} c_\mu \Phi_\mu ,$$
    where μ denotes collectively the quantum numbers and ϕ_μ spin-isospin-HH-radial states
  - In the asymptotic region of large separation between the isolated nucleon $\chi_\gamma(\ell)$ and the cluster ϕ_γ
    $$\Psi \longrightarrow \frac{1}{\sqrt{A}} \sum_{\ell} \phi_\gamma \chi_\gamma(\ell)\, \Phi_{\mathbf{p}}^{(\gamma)}(y_\ell)$$
    $\Phi_{\mathbf{p}}^{(\gamma)}(y_\ell)$ is either a Coulomb distorted wave or simply the plane wave $e^{i\mathbf{p}\cdot y_\ell}$
  - The coefficient of the waves functions are found via variational principles

Ab Initio Calculations via Chiral EFT(III)

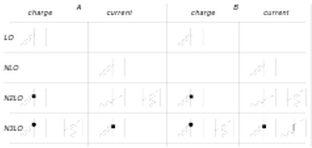
Use chiral effective field theory (χEFT) for nuclear interactions and currents

- Nuclear Hamiltonians include two- and three-nucleon ($2N$, $3N$) interactions derived in χEFT:
  - **N3LO500/N2LO500**: momentum-space non-local $2N$ at N3LO + $3N$ at N2LO with LECs c_D, c_E fitted to triton binding and Gamow-Teller(Epelbaum, 2010), (Machleidt & Entem, 2011)
  - **NVIa/3NIa**: configuration-space local interactions including Δ isobars, with consistent $3N$ forces (Piarulli *et al.*, 2018)



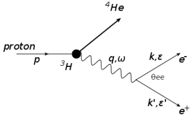
- Corresponding EM current from χEFT
  - (Park *et al.*, 1993,Kölling *et al.*, 2009,Pastore *et al.*, 2009)
  - Including the Δ d.o.f. (Schiavilla *et al.*, 2018)

A = Diagrams in standard χEFT
B = Diagrams with the inclusion of the Δ d.o.f. up to N2LO



^{3}H(p,e^+e^-)^{4}He EM cross section

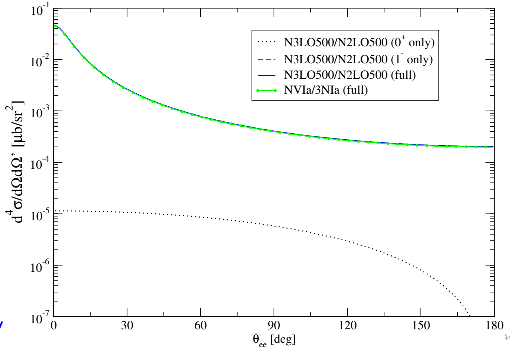
- Explore initially the process as standard EM reaction within a consistent EFT framework



$$\frac{d^6\sigma}{d\epsilon\, d\hat{k}\, d\epsilon'\, d\hat{k}'} = \frac{2\pi}{v}\delta\left(E_0 - \epsilon - \epsilon' - \frac{(\mathbf{p}-\mathbf{q})^2}{2M_4}\right)\sum \left|T_{fi}^{EM}\right|^2,$$

$$T_{fi}^{EM} = 4\pi\alpha\,\frac{(\overline{u}_-\gamma_\mu v_+)j^\mu_{EM}}{q^\mu q_\mu}, \quad j^\mu_{EM} = \langle \Phi_f | J^{\mu\dagger}_{EM} | \Psi_i \rangle$$

- One-photon-exchange approximation
- N3LO500/N2LO500 + χEFT current (Pastore et al., (2009))
- NVIa/3NIa + χEFT current (Schiavilla et al., (2018))
- No possible to explain any large angle "bump"



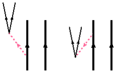
$E_p = 0.9$ MeV

X17 Interaction Currents: Quark and Nucleon Lagrangians

Scalar (S):

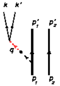
$$\mathcal{L}_q^S = e\,\frac{m_q}{\Lambda_S}\,\bar{q}\,(\varepsilon_0 + \varepsilon_z \tau_3)\,q\,X,$$

$$\mathcal{L}_N^S = \eta_0^S\,\bar{N}NX + \eta_z^S\,\bar{N}\tau_3 NX$$



$$\eta_0^S = \varepsilon_0\left(-\frac{4c_1 m_\pi^2}{\Lambda_S}\right), \quad \eta_z^S = \varepsilon_z\left(-\frac{2c_5 m_\pi^2}{\Lambda_S}\right)$$

Pseudoscalar (P):



$$\mathcal{L}_q^P = e\,\frac{m_q}{\Lambda_S}\,\bar{q}\,(\varepsilon_0 + \varepsilon_z \tau_3)\,i\gamma^5\,q\,X,$$

$$\mathcal{L}_N^P = \eta_0^P\,\bar{N}i\gamma^5 NX + \eta_z^P\,\bar{N}i\gamma^5\tau_3 NX + 2\eta_z^P\,\frac{B_c}{m_\pi^2}\,\bar{N}i\gamma^5\tau_3 X$$

$$\eta_0^P = \varepsilon_0\,\frac{2m_\pi^2 m_N(d_{18} + 2d_{19})}{\Lambda_S}, \quad \eta_z^P = \varepsilon_z\,\frac{f_\pi m_\pi^2}{\Lambda_S}$$

Vector (V):

$$\mathcal{L}_q^V = e\,\bar{q}\,(\varepsilon_0 + \varepsilon_z \tau_3)\,\gamma^\mu\,q\,X_\mu,$$

$$\mathcal{L}_N^V = \eta_0^V\,\bar{N}\gamma^\mu NX_\mu + \eta_z^V\,\bar{N}\gamma^\mu\tau_3 NX_\mu + \text{mag. mom.}$$

$$\eta_0^V = 3\varepsilon_0, \quad \eta_z^V = \varepsilon_z$$

Axial (A):

$$\mathcal{L}_q^A = e\sum_f \varepsilon_f\,\bar{f}\gamma^\mu\gamma^5 f X_\mu,$$

$$\mathcal{L}_N^A = \eta_0^A\,\bar{N}\gamma^\mu\gamma^5 NX_\mu + \eta_z^A\,\bar{N}\gamma^\mu\gamma^5\tau_3 NX_\mu$$

$$\eta_0^A = (3F - D)\varepsilon_0, \quad \eta_z^A = (F + D)\varepsilon_z$$

X17-induced Nuclear Currents

$$T_{fi}^{cX}(N) = 4\pi\alpha \, \frac{\varepsilon_e \, \overline{u}(\mathbf{k}, s) \, \Gamma_c \, v(\mathbf{k}', s') \, j_{fi}^X(N)}{Q^2 - M_X^2} \qquad \Gamma^{c=S,P,V,A} = 1, i\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5 \; ,$$

To account for its width, we make the replacement $Q^2 - M_X^2 \longrightarrow Q^2 - M_X^2 + iM_X\Gamma_X \equiv D_X$

Nucleon-level currents:

$$j_{fi}^{SX}(N) = \overline{u}(\mathbf{p}', s_N') \, u(\mathbf{p}, s_N) \, \chi^\dagger_{t_N'} \, P^{SX} \, \chi_{t_N}$$

$$j_{fi}^{PX}(N) = \frac{\overline{u}(\mathbf{p}', s_N') \, \gamma^\mu\gamma_5 \, iq_\mu \, u(\mathbf{p}, s_N)}{q^2 - m_\pi^2} \, \chi^\dagger_{t_N'} \, P^{PX} \, \chi_{t_N} + \overline{u}(\mathbf{p}', s_N') \, i\gamma^5 \, u(\mathbf{p}, s_N) \, \chi^\dagger_{t_N'} \, \overline{P}^{PX} \, \chi_{t_N}$$

$$j_{fi}^{VX}(N) = -\overline{u}(\mathbf{p}', s_N') \, \gamma^\mu \, u(\mathbf{p}, s_N) \, \chi^\dagger_{t_N'} \, P^{VX} \, \chi_{t_N} + \frac{i}{2m_N} \, \overline{u}(\mathbf{p}', s_N') \, \sigma^{\mu\nu} q_\nu \, u(\mathbf{p}, s_N) \, \chi^\dagger_{t_N'} \, \overline{P}^{VX} \, \chi_{t_N}$$

$$j_{fi}^{AX}(N) = -\overline{u}(\mathbf{p}', s_N') \, \gamma^\mu\gamma_5 \, u(\mathbf{p}, s_N) \, \chi^\dagger_{t_N'} \, P^{AX} \, \chi_{t_N} , \qquad \chi_{t_N}, \chi_{t_N'} = \text{nucleon isospin states}$$

Isospin operators:

$$P^{SX} = \eta_0^S + \eta_z^S \, \tau_3 , \qquad P^{VX} = \eta_0^V + \eta_z^V \, \tau_3 , \qquad P^{AX} = \eta_0^A + \eta_z^A \, \tau_3$$

$$P^{PX} = \frac{g_A}{2f_\pi} \, \eta_z^P \, \tau_3 , \qquad \overline{P}^{PX} = \eta_0^P , \qquad \overline{P}^{VX} = \kappa_0 \, \eta_0^V + \kappa_z \, \eta_z^V \, \tau_3$$

Differential Cross Sections and Electromagnetic Contributions

The total differential cross section for e^+e^- pair production reads:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{\rm EM}}{d\Omega} + \frac{d\sigma_X}{d\Omega} + \frac{d\sigma_{XX}}{d\Omega}$$

Where:

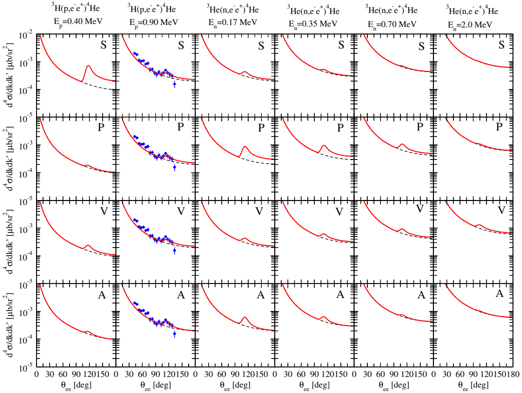
$$\begin{cases} \text{EM term:} & \frac{d\sigma_{\rm EM}}{d\Omega} \sim |T_{fi}^{\rm EM}|^2 \\ \text{Interference:} & \frac{d\sigma_X}{d\Omega} \sim \epsilon_e \left(\frac{T_{fi}^{\rm EM} T_{fi}^{cX*}}{D_X} + cc \right) \\ \text{Pure X17:} & \frac{d\sigma_{XX}}{d\Omega} \sim \epsilon_e^2 \frac{|T_{fi}^{XX}|^2}{|D_X|^2} \end{cases}$$

Dependence on effective couplings $\eta_{0,z}^X$ and $\xi_{0,z}^X$:

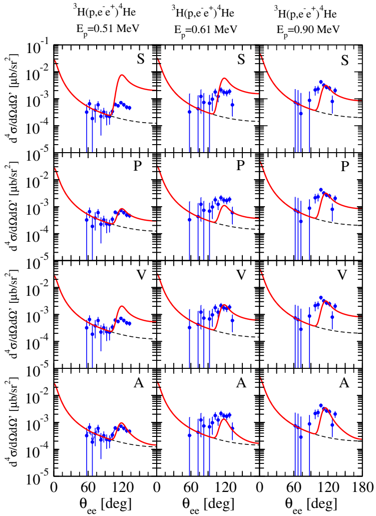
$$\frac{d\sigma_{XX}}{d\Omega} \propto \begin{cases} |\eta_0^S + \eta_z^S \tau_3|^2 & \text{Scalar} \\ |\eta_0^P + \eta_z^P \tau_3|^2 f_P(\theta_{ee}) & \text{Pseudoscalar} \quad \theta_{ee} \equiv \text{angle between lepton pair} \\ |\eta_0^V + \eta_z^V \tau_3|^2 f_V(\theta_{ee}) & \text{Vector} \\ |\eta_0^A + \eta_z^A \tau_3|^2 f_A(\theta_{ee}) & \text{Axial} \end{cases}$$

$^3H(p,e^+e^-)^4He$ and $^3He(n,e^+e^-)^4He$

Pair emission in the perpendicular plane-peak fitted at 0.90 MeV



A. Krasznahorkay et al., (2019)



A. J. Krasznahorkay et al, (2021)

Coupling Constants from ATOMKI 2019 and Comparison with Previous Data

$M_X = 17\text{MeV}$ and $\epsilon_e = 10^{-3}$

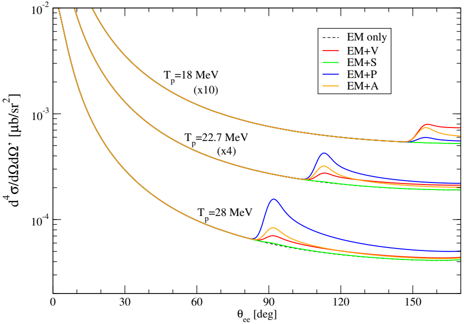
	N3LO500/N2LO500		NVIa/3NIa	
Case	ε_0	ε_z	ε_0	ε_z
Scalar (S)	0.86	**0**	0.75	**0**
Pseudoscalar (P)	**0**	5.06	**0**	4.82
Pseudoscalar (P)	25.5	**0**	27.2	**0**
Vector (V)	2.56×10^{-3}	$-\mathbf{3}\,\varepsilon_0$	2.66×10^{-3}	$-\mathbf{3}\,\varepsilon_0$
Axial (A)	2.58×10^{-3}	**0**	2.89×10^{-3}	**0**

A. Krasznahorkay et al., (2019)

- Vector couplings $\epsilon_{u,d}$ consistent with Feng et al., PRL, (2016) from $^8\mathrm{Be}$ anomaly
- Axial couplings larger than Kozaczuk et al., JHEP, (2016); suppression effects in He nuclear transitions may explain discrepancies
- Pseudoscalar coupling larger than in Delle Rose et al., PRD, (2018); Alves et al., PRD, (2020); origin unclear
- Scalar exchange excluded by earlier analyses
- 2021 ATOMKI data Krasznahorkay et al., PRC, (2021) show larger errors but allow tests at different beam energies:
  - For an axial X17 exchange, the coupling constants appear to be inconsistent with each other

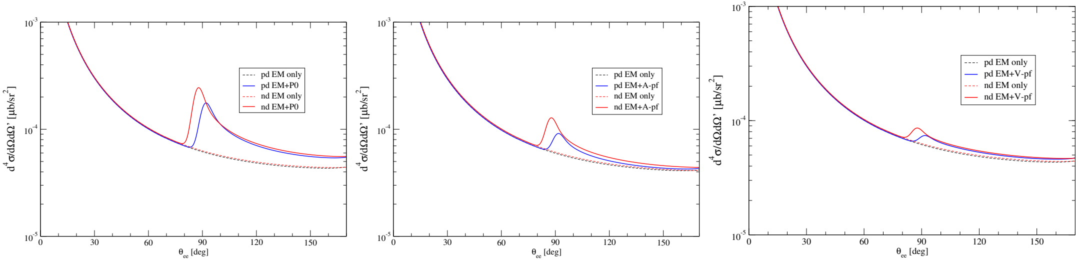
$d(p, e^+e^-)^3$He and $d(n, e^+e^-)^3$H

- X17 production possible only above $E_p > 17.3$ MeV ($E_n > 16.1$ MeV) by kinematic constraints
- The X17 peak moves to lower values of θ_{ee} as the energy increases
- For the S case the contribution is very tiny
- For the P case, the peak becomes more and more evident as the beam energy increases
- The height of the peak due to the V X17 is moreless constant with energy
- In the A case, the height of the peak slightly decreases



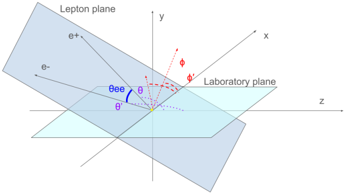
Isospin Structure of X17 Coupling

- Compare $d(p, e^+e^-)^3$He and $d(n, e^+e^-)^3$H
- For protophobic X17, neutron-induced signal is enhanced
- Especially evident in axial coupling scenario

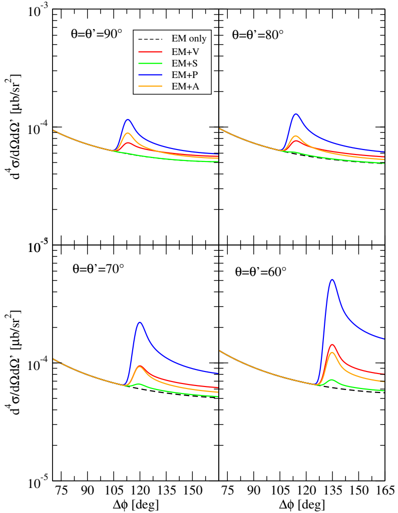


Sensitivity to Azimuthal Angle ϕ

$\Delta\phi = \phi - \phi' =$ azimuthal angles of the two leptons, $\theta(\theta') =$ direction of $e^-(e^+)$



- Angular modulation varies strongly with X17 parity and spin
- Offers a clean handle to discriminate hypotheses



Summary

- Ab initio nuclear inputs critical to assess the signal
- Current predictions motivate new, more precise experiments

Future Perspectives

- Extend the X17–nucleon interaction beyond leading order, including NLO and NNLO contributions in χEFT
- Improve the electromagnetic interaction treatment by including higher-order QED corrections
- Compare theoretical analyses with future measurements

Experimental Suggestions

- Use detectors with large θ and ϕ acceptance
- Perform energy scans (18–30 MeV) to test peak shifts
- Compare p+d and n+d to test isospin dependence