Study of fundamental symmetries in the few-nucleon systems

M. Viviani

INFN, Sezione di Pisa &
Department of Physics, University of Pisa
Pisa (Italy)

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"Perspectives and Challenges in Nuclear Structure after 70 Years of Shell Model"

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Istituto Nazionale di Fisica Nucleare

Outline

The X17 boson "anomaly"

The ATOMKI experiments

- [Krasznahorkay *et al.*, PRL **116**, 042501 (2016)]: "Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson"
- [Krasznahorkay *et al.*, `arXiv:1910.10459` (23 October 2019)]: "New evidence supporting the existence of the hypothetic X17 particle"
- [Krasznahorkay *et al.*, PRC **104**, 044003 (2021)]: "A new anomaly observed in ^{4}He supports the existence of the hypothetical X17 particle"

Reaction	m_X [MeV]	Δm_X (stat) [MeV]	Δm_X (syst) [MeV]	τ [sec]	Evidence
^{7}Li$(p, e^+e^-)^8$Be	16.70	0.35	0.50	10^{-14}	$> 5\sigma$
^{3}H$(p, e^+e^-)^4$He (2019)	16.84	0.16	0.20		$> 7.2\sigma$
^{3}H$(p, e^+e^-)^4$He (2021)	16.94	0.12	0.21		$> 8.9\sigma$

Measurements of the e^+e^- angular correlation in the internal pair conversion (IPC) nuclear transition

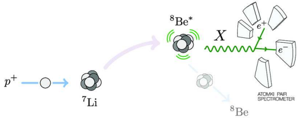


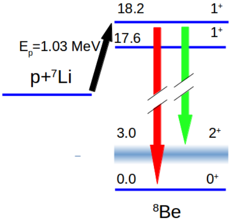
image from [Feng *et al.*, 2016]

Previous "anomalies" found in IPC

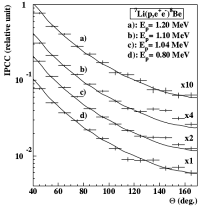
- [de Boer *et al.*, Phy. Lett. **B388**, 235 (1996); J. Phys. G 27 L29 (2001)]: IKF Frankfurt: 9 MeV Boson?
- [Vitéz *et al.*, Acta Physica Polonica B **39**, 483 (2008)]
- [de Boer & Fields, Int. J. mod. Phys. E **20**, 1787 (2011)]

The ^{8}Be experiment

[Krasznahorkay *et al.*, PRL **116**, 042501 (2016)]



Angular distribution of the $e^- e^+$ pair



- [Tanedo, `www.particlebites.com/?p=3970` (Aug. 25, 2016)] “The Delirium over Beryllium”
- [Zhang & Miller, 2017] “Can nuclear physics explain the anomaly observed in the internal pair production in the Beryllium-8 nucleus?”
- Last minute news!!! New paper by the ATOMKI coll. `arXiv:2205.07744`

Process: $^7\mathrm{Li} + p \to (^8\mathrm{Be})^*$

- Radiative capture: $(^8\mathrm{Be})^* \to {}^8\mathrm{Be} + \gamma$
- IPC (standard): $(^8\mathrm{Be})^* \to {}^8\mathrm{Be} + \gamma^* \to {}^8\mathrm{Be} + e^+ e^-$
- IPC (exotic): $(^8\mathrm{Be})^* \to {}^8\mathrm{Be} + X \to {}^8\mathrm{Be} + e^+ e^-$
- Background: real γ converting to $e^+ e^-$ from interaction with the apparatus = external pair conversion (EPC)

The ^{4}He experiment (2019)

- [Krasznahorkay *et al.*, `arXiv:1910.10459v1`], [Firak *et al.*, EPJ Web Conf. **232**, 04005 (2020)]
- [Frankenthal, `https://www.particlebites.com/?p=6696` (Jan. 4, 2020)] "The Delirium over Helium" for an update of the precedent *particlebites.com* report
- `cerncourier.com/a/rekindled-atomki-anomaly-merits-closer-scrutiny/`
- Reaction $^3\mathrm{H}(p, e^- e^+)^4\mathrm{He}$, proton beam of 0.90 MeV

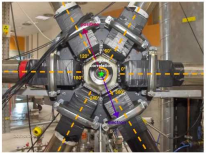
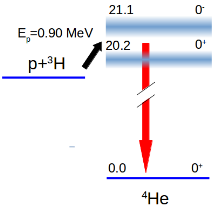
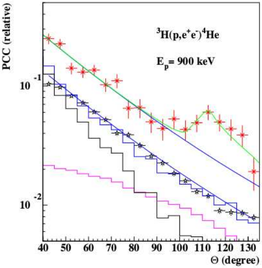


Figure 3. The Atomki nuclear spectrometer. This is an upgraded detector



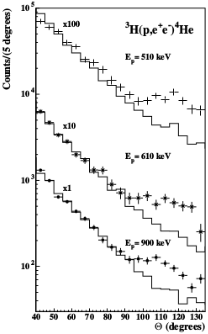
Angular distribution of the $e^- e^+$ pair (IPC+EPC)



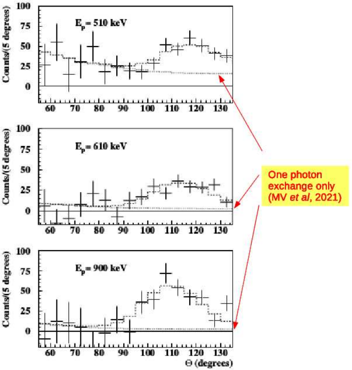
The ^{4}He experiment (2021)

- [Krasznahorkay *et al.*, PRC **104**, 044003 (2021)]
- Reaction $^3\mathrm{H}(p, e^- e^+)^4\mathrm{He}$, now 3 energies of the proton beam: 0.51, 0.61, and 0.90 MeV

Measured angular distribution of the $e^- e^+$ pairs



GEANT analysis: Subtraction of the background of pairs created EPC processes



These announcements triggered new expt. activities . . .

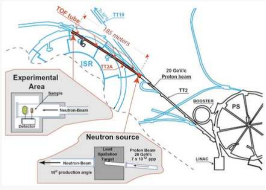
Courtesy by C. Gustavino (INFN-Rome)

Experiment	
LHCb	Charm meson decay $D^*(2007)^0 \to D^0 A'$ $A' \to e^- e^+$
Mu3e	Muon decay channel $\mu^+ \to e^+ \nu_e \overline{\nu_\mu}$ ($A' \to e^- e^+$)
VEPP-3	$e^- e^+ \to A' \gamma$
KLOE-2	$e^- e^+ \to \gamma (X \to e^- e^+)$
MESA	e- beam on gaseous target, to produce A'
Darklight	e- scattering of H gas target, to produce A'
HPS	e- beam on W to study $A' \to e^- e^+$ and $A' \to \mu^- \mu^+$
PADME	e+ beam on diamond target $e^- e^+ \to X\gamma$
NA64	$eZ \to eZ + X17$
NSL	^{8}Be ($A' \to$ e-e+)
^{8}BeP	^{8}Be ($A' \to$ e-e+)
New JEDI	^{8}Be/^{3}He/d... ($A' \to$ e-e+)
Montréal	^{8}Be ($A' \to$ e-e+)
NSCL	^{8}Be ($A' \to$ e-e+)
IUAP CTU	^{8}Be and ^{4}He ($A' \to$ e-e+)
n_TOF	**^{4}He and ^{8}Be ($A' \to$ e-e+) (proton and neutron beams)**
MEG2	^{8}Be
NUCLEX	^{8}Be

In particular in Italy . . .

- PSI: $^7\mathrm{Li}(p, e^+e^-)^8\mathrm{Be}$ MEGII (data taking underway)
- n_ToF at CERN: $^3\mathrm{He}(n, e^+e^-)^4\mathrm{He}$ (planned in 2023)
- LNL: $^7\mathrm{Li}(p, e^+e^-)^8\mathrm{Be}$ NUCLEX (planned in 2023)
- in investigation: $^2\mathrm{H}(n, e^+e^-)^3\mathrm{H}$ (n_ToF) and $^2\mathrm{H}(p, e^+e^-)^3\mathrm{He}$ (LNGS)

n_ToF CERN



and theoretical speculations...

- [Feng *et al.*, 2016] "Protophobic Fifth Force Interpretation of the Observed Anomaly in $^8\mathrm{Be}$ Nuclear Transitions"
- [Kozaczuk, Morrissey, & Stroberg, 2016] "Light axial vector bosons, nuclear transitions, and the ^{8}Be anomaly"
- [Delle Rose, Khalil, & Moretti, 2019] "New Physics Suggested by Atomki Anomaly"
- [Feng, Tait, & Verhaaren, 2020] "Dynamical Evidence For a Fifth Force Explanation of the ATOMKI Nuclear Anomalies"
- [Fayet, 2020] "The U boson, interpolating between a generalized dark photon or dark Z, an axial boson and an axionlike particle"
- [Alves, 2020] "Signals of the QCD axion with mass of 17 MeV/c^2: Nuclear transitions and light meson decays"
- "Shedding light on X17", workshop held at Centro Fermi, Rome, Sep 6–8, 2021
- [Wong, 2022] "QED Meson Description of the X17 and Other Anomalous Particles"

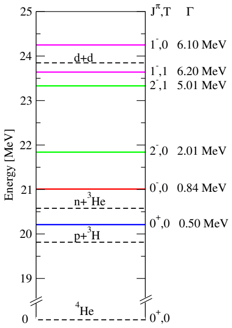
Most of the speculations based on "resonance saturation"
Assumed mechanism $p + {}^3\mathrm{H} \to ({}^4\mathrm{He})^* \to {}^4\mathrm{He} + X$,
followed by the decay $X \to e^+e^-$

Present calculation

Motivation of this work:

- solve accurately the $A = 4$ nuclear dynamics
- include the contribution of all relevant waves
- treat the X17 interaction within the χPT framework

0^+ and 0^- resonances: very sensitive to the nuclear interaction



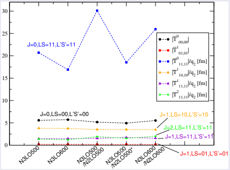
[Tilley, Weller, & Hale, 1992]

For the 0^+ resonance:

[Bacca *et al.*, 2015], [Kegel *et al.*, 2022]

For the 0^- resonance:

- $\vec{n} + {}^3\mathrm{He} \to p + {}^3\mathrm{H}$ "n3he" experiment at ORNL at $E_n = 4.6$ meV
- $A_y = (-41 \pm 5.6 \text{ stat} \pm 0.6 \text{ sys}) \cdot 10^{-8}$



X17 interaction with electrons

- $\Gamma = 1, \gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \ldots$
- e =electric charge ($e > 0$)
- $X(x)$ X17 field

$$\mathcal{L} = e\varepsilon_e \bar{e}(x)\Gamma e(x) X(x) + e\varepsilon_u \bar{u}(x)\Gamma u(x) X(x) + \cdots$$

X17 decay

- $X \to e^- e^+, \nu\bar{\nu}, \ldots$
- Decay channel in $e^- e^+$ dominant [Feng *et al.*, 2016–2020]
- $\Gamma_X \approx \varepsilon_e^2 \alpha M_X$
- The X17 must decay in the apparatus $\to |\varepsilon_e| > 10^{-5}$
- Beam dump experiments:
  - SLAC E141 $|\varepsilon_e| > 2\ 10^{-4}$ [Alexander *et al.*, 2017]
  - NA64 $|\varepsilon_e| > 6.8\ 10^{-4}$ [Banerjee *et al.*, 2020]
- Direct search in $e^- e^+$ experiments: KLOE2 $|\varepsilon_e| < 2\ 10^{-3}$ [Feng *et al.*; 2016]

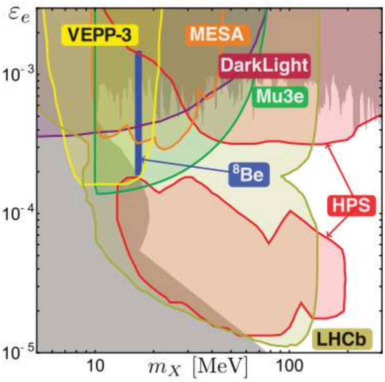


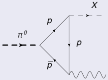
image from [Feng *et al.*, 2016]

Proposed models

“Protophobic” vector boson
[Feng *et al.*, 2016–2020]
Fifth force

Quantum numbers $J^\pi = 1^-$

NA48 limit for $\pi^0 \to \gamma X$
[Batley *et al.*, 2015]
A way out: the particle X does not couple with protons
$|2\varepsilon_u + \varepsilon_d| < 8\ 10^{-4}$



Relation with $a_e = (g-2)_e/2$

- New estimate of α [Morel *et al.*, 2020]
- $\to \delta a_e = (4.8 \pm 3.0) \times 10^{-13} (+1.6\sigma)$
- Contribution of a vector boson X17: $\delta a_e > 0$
- Consistent with the ^{8}Be anomaly!

“Piophobic” axion [Alves, 2020]

Quantum number $J^\pi = 0^-$

QCD axion with mass ~ 17 MeV generally excluded
[Alves & Weiner, 2017]
A way out: no mixing with π^0
$\mathcal{L} = \theta_{a-\pi} X(x) \pi^0(x)$,
$|\theta_{a-\pi}| < 10^{-4}$

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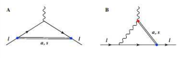
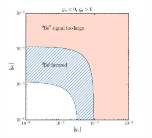


Light axial vector [Kozaczuk, Morrissey, & Stroberg, 2016]

Quantum number $J^\pi = 1^+$

In this case the NA48 limit does not apply



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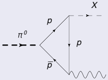

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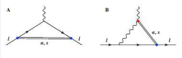

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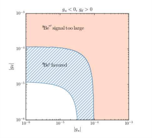

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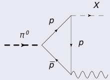

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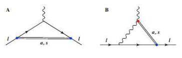

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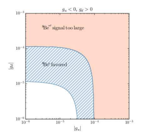

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Theoretical study of $A = 4$ reactions

Numerical techniques for $A = 4$ for scattering

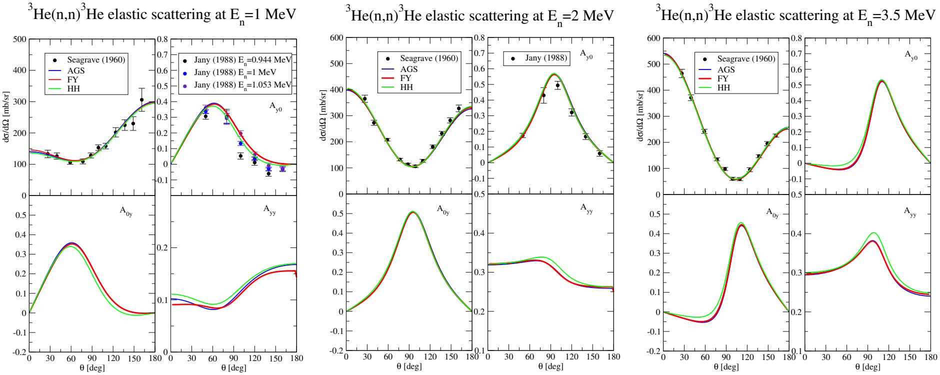
- Faddeev-Yakubovsky methods [Lazauskas & Carbonell, 2004], [Deltuva & Fonseca, 2007]
- Expansion on a basis: NCSM [Quaglioni, Navratil & Roth, 2010], Gaussians [Aoyama *et al.*, 2011], R-matrix [Descouvemont & Baye], HH [Kievsky, Marcucci, MV, *et al.*, 2008], ...

Modern nuclear interactions

- Based on χEFT & χ–perturbation theory [Weinberg, 1966], [Callan *et al.*, 1969], [Gasser & Leutwyler, 1984]
- Expansion parameter Q/Λ_χ, $Q \sim m_\pi$, $\Lambda_\chi \approx 1$ GeV [Weinberg,1990-1992], [Ordoñez, Ray, & Van Kolck, 1996], [Epelbaum, Hammer, & Meissner, 2009] for a review
- NN interaction:
  - Lowest order (LO) $(Q/\Lambda_\chi)^0$: one-pion-exchange potential + contact interactions
  - next-to-leading (NLO): 1 loop+dimensional regularization, etc
  - The various contributions can be visualized through TOPT diagrams
  - Cutoff $\Lambda = 400 - 600$ MeV for the non-perturbative regularization: the results should not depend on it
- 3N interaction: developed at N4LO, but for the moment practical calculations are possible only at N2LO

Benchmark test of 4N scattering calculations

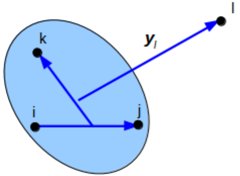
N3LO500 potential – ^{3}He$(n,n)^3$He elastic scattering



AGS= Deltuva & Fonseca – FY= Lazauskas & Carbonell – HH= present work

Calculation of transition amplitudes

We need 1) initial/final wave functions 2) transition operators (currents & charges)



Initial/final wave functions

Ψ_4: ^{4}He bound state wave function $J^\pi = 0^+$

Ψ_{1+3}: scattering wave function – decomposed in components of definite LSJ

$$\Psi_{1+3} = \sum_{LMSS_zJJ_z} (\frac{1}{2}m_3\frac{1}{2}m_1|SS_z)(LMSS_z|JJ_z)4\pi i^L Y^*_{LM}(\hat{p})e^{i\sigma_L}\Psi^{LSJ}_{1+3}$$

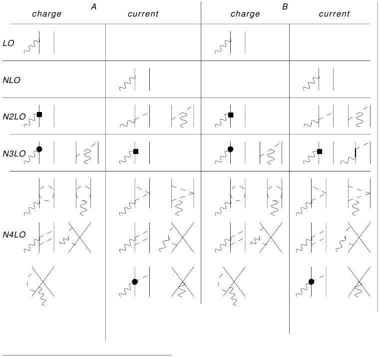
$\boldsymbol{p}$ relative momentum

EM charge & currents transition operators

EM current from χEFT

[Park *et al*, 1993], [Kolling *et al*, 2009], [Pastore *et al*, 2009]
Including the Δ d.o.f. [Schiavilla *et al.*, 2018]

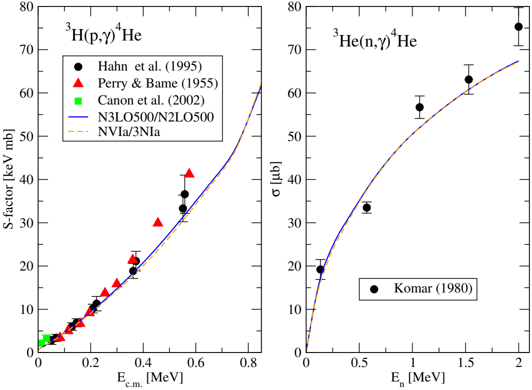
A= Diagrams in standard χEFT
B= Diagrams with the inclusion of the Δ d.o.f. up to N2LO



$^3\mathrm{H}(p,\gamma)^4\mathrm{He}$ and $^3\mathrm{He}(n,\gamma)^4\mathrm{He}$ EM captures

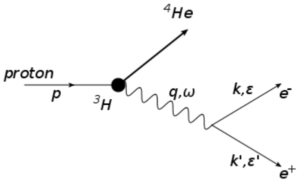
Interest

- BBN, production of $^4\mathrm{He}$
- Dominated by the E_1 transition $1^- \to 0^+$
- No sensivity to interactions/MEC
- Real γ's conversion in $e^- e^+$ from interaction with the apparatus
- $\to$ external pair convertion (EPC)



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

"Standard" EM process



$$\frac{d^6\sigma}{d\epsilon d\hat{k} d\epsilon' d\hat{k}'} = \frac{\alpha^2}{8\pi^3}\frac{kk'}{Q^4 v}\delta\left(E_0 - \epsilon - \epsilon' - \frac{(\boldsymbol{p}-\boldsymbol{q})^2}{2M_4}\right) \times \sum_i v_i R_i(q,\omega)$$

$E_0 = E_p + B_4 - B_3 \approx 20$ MeV, $\boldsymbol{q} = \boldsymbol{k} + \boldsymbol{k}'$, $\omega = \epsilon + \epsilon'$, $Q^2 = \omega^2 - q^2 > 0$ "time-like"
$\cos\theta_{ee} = \hat{k}\cdot\hat{k}'$, $i = L, T, TT, TT', LT, LT'$

$$v_L = \frac{Q^4}{q^4}(\epsilon\epsilon' + \boldsymbol{k}\cdot\boldsymbol{k}' - m_e^2) \qquad R_L(q,\omega) = \sum_{m_1,m_3} |\langle\Psi_4|\rho(\boldsymbol{q})^\dagger|\Psi^{(pt)}_{m_1,m_3}\rangle|^2 \sim \sum_{LSJ}|C_J^{LSJ}|^2$$

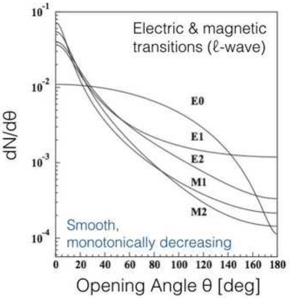
After integrating the δ over ϵ' and numerically over ϵ ($p_r = \epsilon'(k' - p\cos\theta' + k\cos\theta_{ee})/k'$)

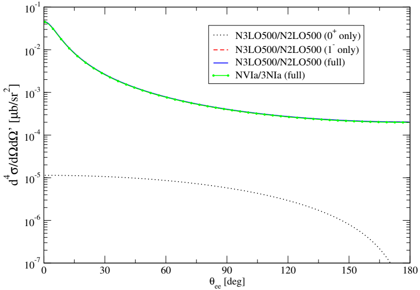
$$\frac{d^4\sigma}{d\hat{k}d\hat{k}'} = \frac{\alpha^2}{8\pi^3}\int_{m_e}^{\epsilon max} d\epsilon \left[\frac{kk'}{Q^4 v}\frac{1}{1+p_r/M_4}\sum_i v_i R_i\right]_{\epsilon'\approx E_0-\epsilon}$$

^{3}H(p, e^+e^-)^{4}He cross section in the one-photon-exchange approximation

Calculation using
N3LO500/N2LO500 + χEFT current by
[Pastore *et al.*, 2009]
NVIa/3Na* + χEFT current by [Schiavilla *et al.*, 2018]

Multipole angular distribution as reported in
[Tanedo,
`www.particlebites.com/?p=3970`]





Due to the simple q dependence of the matrix elements, it is not possible to explain any large angle "bump"

Incorporating the X17

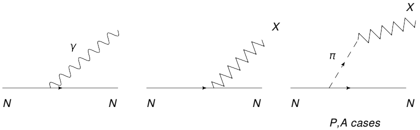
Scales ...

- $E \sim 1$ TeV BSM mechanism (axion, SSM, ...)
- $E \sim 1$ GeV: interaction with SM particles
- $E \sim 100$ MeV: interaction with hadrons (N, π, ...)
- $E \sim 1$ MeV: nuclear physics experiments

EFT approach

1. Start with a generic interaction Lagrangian with electrons, *u* and *d* quarks, ...
2. Generate the interaction at hadronic level using χEFT
3. Accurately compute the matrix elements of the generated operators

Analysis similar to what done for DM interaction with nuclei
[Menéndez *et al.*, 2011-2012], [Hoferichter *et al.*, 2015–2019], [Bishara *et al.*, 2016], [Körber *et al.*, 2017], [Nogga *et al.*, 2017], [Andreoli *et al.*, 2019], [Hu *et al.*, 2021], ...
For X17: LO (+ some subleading terms) analysis [MV *et al.*, PRC **105**, 014001 (2022)]



LO (+ some subleading terms) analysis: S case

[MV *et al.*, PRC **105**, 014001 (2022)]

Scalar case at 1 GeV scale

$$\mathcal{L}^S_{q,X}(x) = \sum_{f=u,d} e\, \frac{\varepsilon_f\, m_f}{\Lambda}\, \bar{f}(x) f(x)\, X(x)\,,$$

At hadronic level

$$\mathcal{L}^S_X(x) = e\,\overline{N}(x)[\eta^S_0 + \eta^S_z\,\tau_3]N(x)\,X(x)$$

$$\eta^S_0 = -\frac{4\,c_1\,m_\pi^2}{\Lambda_S}\,\varepsilon_0$$

$$\eta^S_z = -\frac{2\,c_5\,m_\pi^2}{\Lambda_S}\,\varepsilon_z$$

$$\varepsilon_0 = \frac{\Lambda_S}{\Lambda}\,\frac{m_u\,\epsilon_u + m_d\,\epsilon_d}{2\,m_q}$$

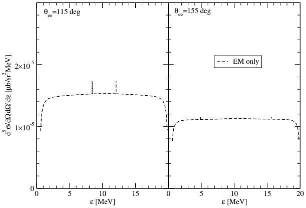
$$\varepsilon_z = \frac{\Lambda_S}{\Lambda}\,\frac{m_u\,\epsilon_u - m_d\,\epsilon_d}{2\,m_q}$$

- Λ high energy scale ($\approx$ 246 GeV)
- $\Lambda_S = 1$ GeV introduced for convenience
- Extended to treat also pseudoscalar (P), vector (V), and axial (X) bosons

X17-induced cross section

$$\frac{d^5\sigma}{d\epsilon\, d\hat{\mathbf{k}}\, d\hat{\mathbf{k}}'} = \sigma_{EM}(\epsilon) + \varepsilon_e \left[\frac{R_X(\epsilon)}{D_X} + \text{c.c.} \right] + \varepsilon_e^2 \frac{R_{XX}(\epsilon)}{|D_X|^2} = \sigma_{EM}(\epsilon) + \frac{\varepsilon_e \left[R_X(\epsilon)\, D_X^* + \text{c.c.} \right] + \varepsilon_e^2\, R_{XX}(\epsilon)}{|D_X|^2}$$

$\epsilon =$ electron energy



$$\frac{1}{|D_X|^2} \to \frac{\pi}{|\alpha_i|} \frac{1}{\Gamma_X M_X} \delta(\epsilon - \epsilon_i)\ .$$

- Propagator of a massive particle $1/D_X = 1/(Q^2 - M_X^2)$, where $Q^2 = (k + k')^2$
- $M_X \to M_X - i\frac{\Gamma_X}{2}$
- Γ_X from the process $X \to e^+ e^-$
  - $\Gamma_X = \varepsilon_e^2 \alpha M_X \sim 1$ eV
- Condition $Q^2 - M_X^2 = 0$ verified for $\epsilon = \epsilon_i$, $i = 1, 2$
- For $\epsilon \approx \epsilon_i$, $Q^2 - M_X^2 = \alpha_i(\epsilon - \epsilon_i)$

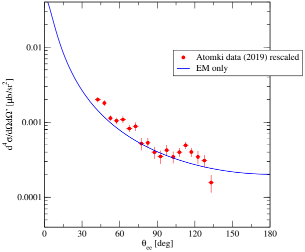
$$\frac{d^4\sigma}{d\hat{\mathbf{k}}\, d\hat{\mathbf{k}}'} = \left[\int_{m_e}^{E_{max}} \sigma_{EM}(\epsilon) \right] + \sum_i \left[2\varepsilon_e \Im\Big(R_X(\epsilon_i)\Big) \frac{\pi}{|\alpha_i|} + \varepsilon_e^2\, R_{XX}(\epsilon) \frac{\pi}{|\alpha_i| M_X \Gamma_X} \right]$$

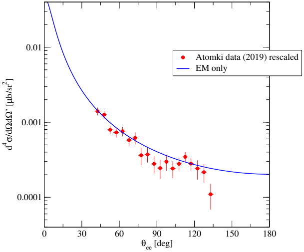
No sensitivity to ε_e and the interference term!!!

Fit of the 2019 data

- In the perpendicular plane, the X17 signal appears for $\theta_{ee} > 110^\circ$
- only a counting rate is fournished – no information on the flux/target/efficiencies
- Procedure:
  - rescale the ATOMKI rate by a factor so to reproduce the cross section for $\theta_{ee} < 110^\circ$
  - For these angles the cross section is EM only - no unknown parameter
  - Fix M_X, ε_u, ε_d to reproduce the "bump"

Problem!

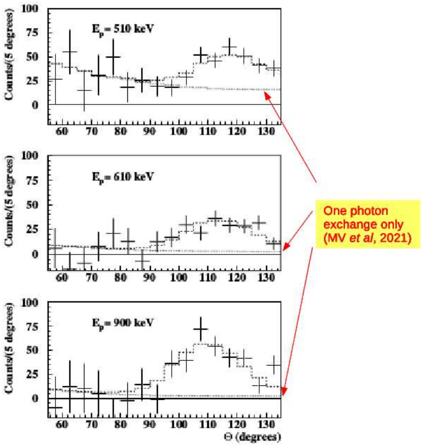




Here there is also the problem of the EPC pairs!

Fit of the 2021 data

- 2021 data: the background has been somehow subtracted
- but the procedure it is still difficult to be applied
- Furthermore: finite angular/energy resolution of the target, geometry of the detector, efficiencies, etc.

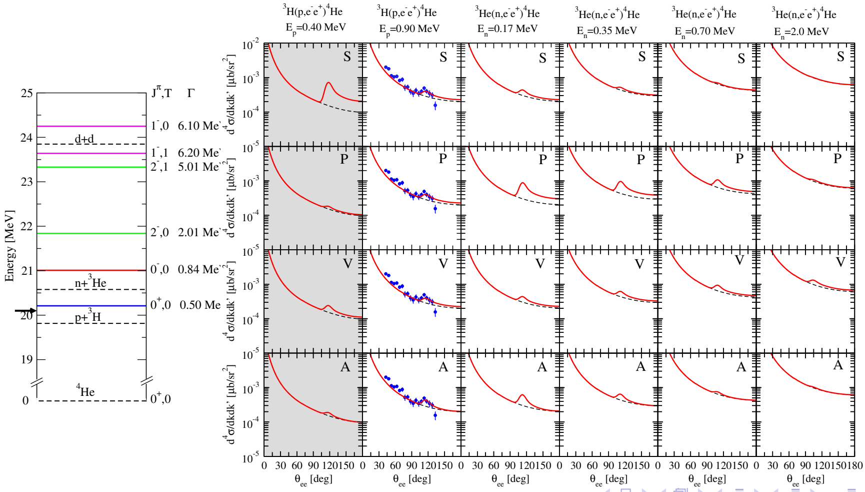


For the moment

- let us study he dependence of the cross section on
  - beam energy
  - the e^+e^- emission angles
- see if it is possible to extract information on the hypothetical X17

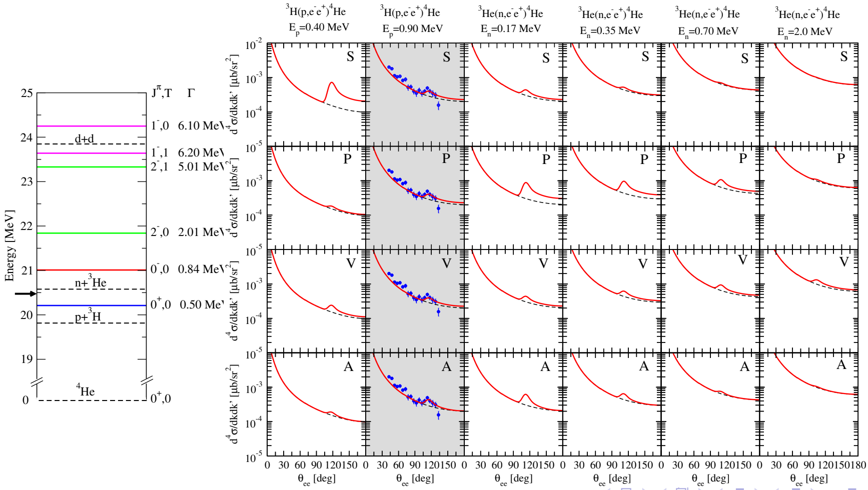
Comparison with the 2019 ATOMKI data

pair emission in the perpendicular plane – peak fitted at 0.90 MeV



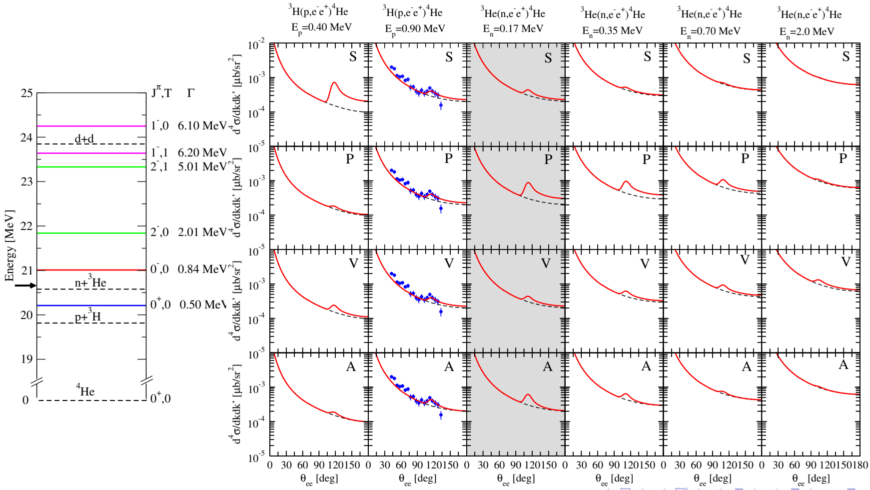
Comparison with the 2019 ATOMKI data

pair emission in the perpendicular plane – peak fitted at 0.90 MeV



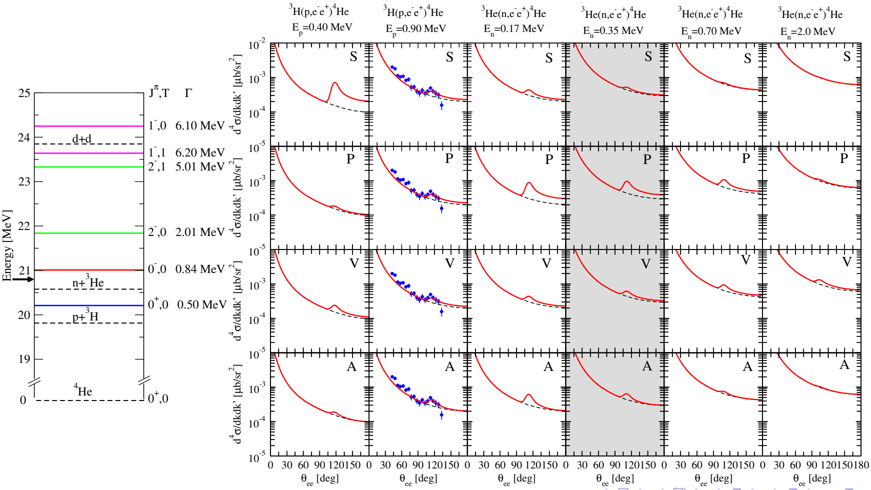
Comparison with the 2019 ATOMKI data

pair emission in the perpendicular plane – peak fitted at 0.90 MeV



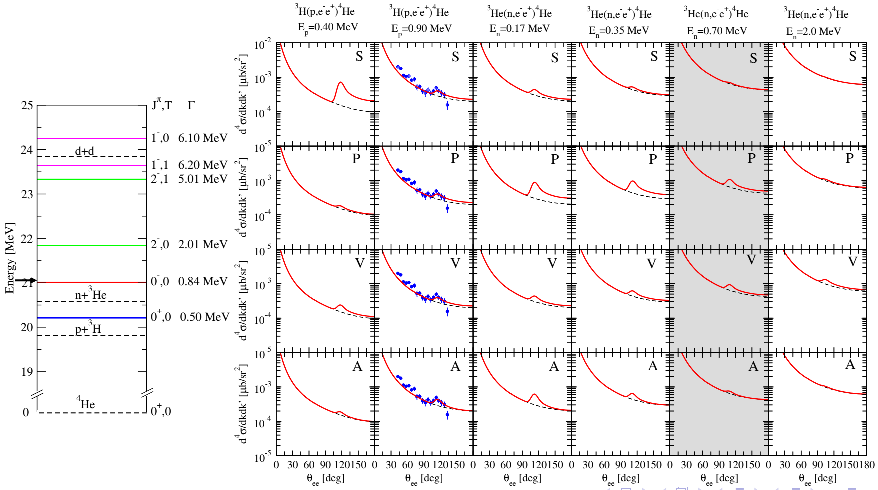
Comparison with the 2019 ATOMKI data

pair emission in the perpendicular plane – peak fitted at 0.90 MeV



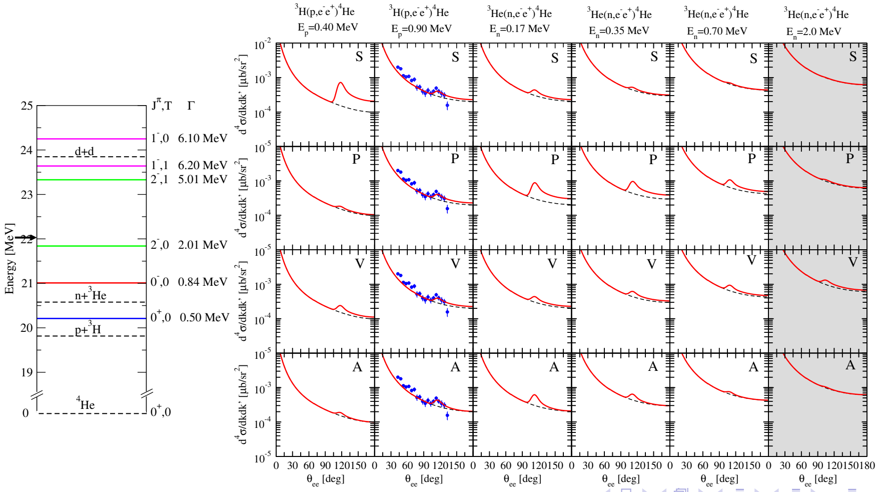
Comparison with the 2019 ATOMKI data

pair emission in the perpendicular plane – peak fitted at 0.90 MeV



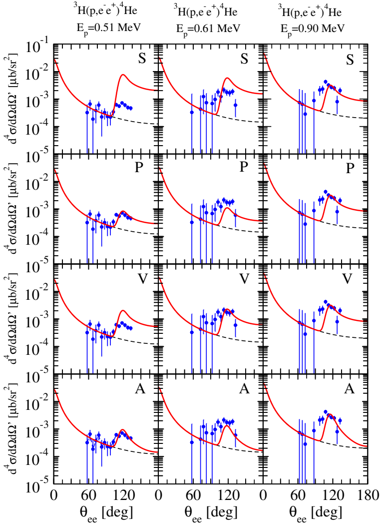
Comparison with the 2019 ATOMKI data

pair emission in the perpendicular plane – peak fitted at 0.90 MeV



Comparison with the 2021 ATOMKI data

pair emission in the perpendicular plane – peak fitted at 0.90 MeV



Extracted coupling constants

S,P cases
$$\varepsilon_{0,z} = \frac{\Lambda_S}{\Lambda} \frac{m_u\varepsilon_u \pm m_d\varepsilon_d}{2m_q}$$

V,A cases
$$\varepsilon_{0,z} = \frac{\varepsilon_u \pm \varepsilon_d}{2}$$

Protophobic case
$$\left[2\varepsilon_u + \varepsilon_d = 0 \Rightarrow 3\varepsilon_0 + \varepsilon_z = 0\right]$$

	N3LO500/N2LO500		NVIa/3NIa	
Case	ε_0	ε_z	ε_0	ε_z
S	0.86×10^0	**0**	0.75×10^0	**0**
P	**0**	5.06×10^0	**0**	4.82×10^0
P	2.55×10^1	**0**	2.72×10^1	**0**
V	2.56×10^{-3}	$-\mathbf{3}\,\boldsymbol{\varepsilon}_0$	2.66×10^{-3}	$-\mathbf{3}\,\boldsymbol{\varepsilon}_0$
A	2.58×10^{-3}	**0**	2.89×10^{-3}	**0**

First rough estimates – very uncertain due to the aforementioned difficulties

Vector case

- $|\varepsilon_{u,d}| \sim 10^{-3}$ Feng *et al.*, 2016-2020]
- Consistent!

Pseudoscalar case

- $|\varepsilon_{u,d}| \sim 1$ Alves, 2020], Delle Rose *et al.*, 2019]
- too small!

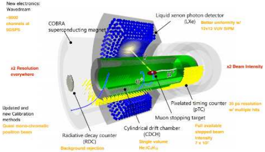
Axial case

- $|\varepsilon_{u,d}| \sim 10^{-4}$ [Kozaczuk, Morrissey, & Stroberg, 2016]
- too small!

^{8}Be experiment at PSI

Courtesy by A. Papa (INFN-Pisa) and F. Renga (INFN-RM1)

Search for possible $\mu \to e$ transition



Proton beam used to test the apparatus

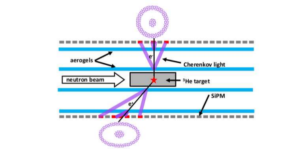
MEGII CW accelerator and Fifth force target

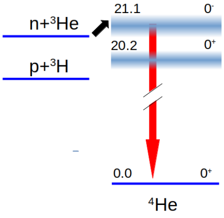
- Data taking underway!!!
- Beam energy 1.2 MeV
- Thick target $T_p = 1.2 \to 0.8$ MeV
- First results expected this year
- In progress: Theoretical effort to analyze the data (see the last part of the talk)

^{4}He experiment at CERN

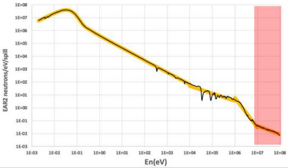
^{3}He$(n, e^+e^-)^4$He using the neutron beam of the n_ToF experiment
[MV *et al.*, PRC **105**, 014001 (2022)]

- neutron energy tagged by means of the time-of-flight
- background:
  - ^{3}He$(n, n)^3$He
  - ^{3}He$(n, p)^3$H: the most dangerous problem $\sigma_{(n,p)} \gg \sigma_{\rm IPC}$
  - ^{3}He$(n, \gamma)^4$He followed by EPC
- Energy of the leptons is of several MeV: $\beta \sim 1$
- Energy of the protons $\sim$ a few MeV: $\beta \ll 1$
- Cherenkov [C. Gustavino *et al.*, 2021]





Neutron energies



Conclusions and perspectives

Analysis of the $^4\mathrm{He}$ ATOMKI "anomaly"

- Accurate description of the nuclear dynamics using state-of-the-art techniques
- Test with $p + {}^3\mathrm{H}$ and $n + {}^3\mathrm{He}$ EM captures data: OK!
- Contribution of the 1^- wave very significant at all energies
- Inclusion of the possible emission of an X17, vs. the beam energy and the emission angles

Perspectives

- New $^8\mathrm{Be}$ experiment underway at PSI
  - Analysis of the $^7\mathrm{Li}(p, e^+e^-)^8\mathrm{Be}$ process using GFMC calculation of $^8\mathrm{Be}$ ground/excited states
- Collaboration with the n_ToF group
  - analysis of the $^3\mathrm{He}(n, e^-e^+)^4\mathrm{He}$ process
  - technical design in progress & GEANT analysis currently in progress
- $^2\mathrm{H}(n, e^+e^-)^3\mathrm{H}$ and $^2\mathrm{H}(p, e^+e^-)^3\mathrm{He}$ reactions to test the protophobic hypothesis
- Study of possible "standard" explanation
  - Two-photon exchange contribution [Aleksejevs *et al.*, 2021] for $^4\mathrm{He}$ & $^8\mathrm{Be}$
- If the anomaly is confirmed, full χEFT treatment of the X17-nucleon interaction
- Analysis of CP-violating X17 interactions and relation to EDM's

Collaborators

Theoretical group

- A. Kievsky, & L.E. Marcucci - *INFN-Pisa & UniPI, Pisa*
- L. Girlanda *UniSalento & INFN-Lecce, Lecce*
- E. Filandri *UniTN, Trento*
- R. Schiavilla *ODU, Norfolk, and Jefferson Lab., Newport News*
- G. King & S. Pastore *WU, St. Louis*
- G. Salmè INFN-RM1, Rome

n_ToF Working group

n_TOF:
- G. Gervino (UNITO)
- P. Mastinu (INFN LNL)
- C. Gustavino (INFN ROMA)
- A. Mengoni (ENEA)
- C. Massimi (UNIBOLOGNA)
- N. Colonna (INFN BARI)
- S. Fiore (ENEA ROMA)
- A. Mazzone (CNR BARI)
- M.C. Petrone (IFIN-HH BUCHAREST)

Theoretical group:
- L. E. Marcucci (UNIPISA)
- M. Viviani (INFN PISA)
- A. Kievsky (INFN PISA)
- L. Girlanda (UNISALENTO)

Detector R&D:
- E. Cisbani (ISS)
- F. Renga (INFN ROMA)

Working group (in evolution)

Thank you for your attention!

BACKUP SLIDES

Violation of the time-reversal symmetry

Interest: Matter-antimatter asymmetry [Sakharov, 1967] $\rightarrow$ CP violation

At a high energy scale

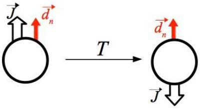
- In the Standard Model (SM)
  - phase in the CKM matrix (too small)
  - possible phase in the neutrino mixing matrix (?)
  - θ-term: From $d_n < 2.9 \cdot 10^{-13} e$ fm [Baker *et al.*, 2006] $\rightarrow |\theta| < 10^{-10}$ Strong CP problem
- Beyond Standard Model (BSM) dimension 6 possible terms
  - Weinberg three-gluon operator
  - quark EDM term
  - quark chromo-EDM term
  - four-quark operators
- See [De Vries *et al.*, FIP **8**, 218 (2020)] for a review

At the nuclear energy scale

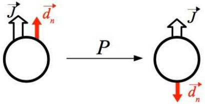
- Nucleons and pions d.o.f.
-
  - TV nucleon-pions vertices $g_{0\div 2}$
  - Three-pion vertex Δ
  - Nucleon EDMs d_p, d_n
  - Nucleon-nucleon contact terms $C_{1\div 5}$
- it is possible (but difficult) to relate these LEC's with those appearing in SM and BSM
- Many parameters $\Rightarrow$ many measurements are needed!

Electric dipole moments (EDMs)

For an "elementary" particle $\boldsymbol{d} \propto \boldsymbol{J}$



EDM $\Rightarrow \vec{d}_n = q\,\vec{r}$



If P and T are conserved $\Rightarrow \langle \vec{d}_n \rangle = 0$

- Existing measurements:
  - Electron $|d_e| < 10^{-15} e$ fm [ACME, 2014]
  - Neutron $|d_n| < 2.9 \cdot 10^{-13} e$ fm [Baker *et al.*, 2006]
  - Heavy nuclei ^{199}Hg, pear-shaped nuclei
- EDMS predicted by the CKM phase are 5-6 orders of magnitude smaller
- New observables
  - EDMs of charge particles (p, d, ^{3}H, ^{3}He) up to $\sim 10^{-16} e$ fm in dedicated storage-rings [Y. K. Semertzidis, 2011]
  - $\vec{n}\vec{A}$ scattering $\Rightarrow$ amplified by nuclear resonances [Gudkov, 1992]

EDMs of light nuclei

Solution of $H\Psi = E\Psi$ including components of both parities and then computing $\langle\Psi|\sum_{i=1}^{A} e_i \boldsymbol{r}_i|\Psi\rangle$

$$d^A = d_p a_p + d_n a_n + g_0 a_0 + g_1 a_1 + g_2 a_2 + C_1 A_1 + C_2 A_2 + C_3 A_3 + C_4 A_4 + C_5 A_5 + \Delta a_\Delta$$

Deuteron

a_p	0.939
a_n	0.939
a_1 [fm]	0.200
A_3 [fm]	0.013
A_4 [fm]	−0.013
a_Δ [fm]	−0.304

^{3}H and ^{3}He

	^{3}H	^{3}He
a_n	−0.033	0.908
a_p	0.909	−0.033
a_0 [fm]	−0.053	0.054
a_1 [fm]	0.158	0.158
a_2 [fm]	−0.119	0.119
A_1 [fm]	0.006	−0.006
A_2 [fm]	−0.010	0.010
A_3 [fm]	−0.008	−0.008
A_4 [fm]	0.013	0.013
A_5 [fm]	−0.022	0.022
a_Δ [fm]	−0.343	−0.339

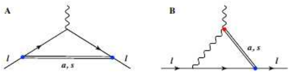
Relating X17, EDM's, $(g-2)_l$, ...

Browsing `ArXiv:hep-ph`, one can find several "interesting" models
Consider, for example, [Marciano *et al.*, 2016], [Cornella *et al.*, 2019], [Di Luzio *et al.*, 2021]
including CP violating terms in the X17 Lagrangian

$$\mathcal{L} = \sum_{i=e,\mu,u,d,\ldots} \left[g_{ii} \overline{\psi}_i (1-\gamma^5)\psi_i + h.c. \right] X + \frac{1}{4} g X F^{\mu\nu} F_{\mu\nu} + \frac{1}{4} \tilde{g} X F^{\mu\nu} \widetilde{F}_{\mu\nu}$$

Contributions to

- Atomki experiments
- $(g-2)_e$ and $(g-2)_\mu$
- EDM's of e, μ, neutron, nuclei



"In summary, a CPV ALP can be related to many fundamental open questions in particle physics"
[Di Luzio *et al.*, 2021]