# Fifth Force in Atomic Systems: Where to Look

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# Abstract

*Recently, the so-called X17 boson may have been seen in nuclear physics experiments at the ATOMKI institute in Debrecen, Hungary. The mass range of the particle, which is about 17 MeV, hence its name, makes the particle hard to detect in low-energy atomic physics experiments, despite the unprecedented accuracy of modern experiments. We find the effective Hamiltonians generated by X17 exchange, for both the pseudoscalar as well as the vector hypothesis. The general conclusion of our investigations is that the X17-mediated effects should be most visible in the shift of hyperfine sublevels, and rather leave the Lamb shift invariant. Our findings, summarized in Physical Review A* **101***, 062503 (2020), have further implications for the search of new forces in high-precision atomic spectroscopy experiments.*

## Motivation (Group of Attila Krasznahorkay, ATOMKI)

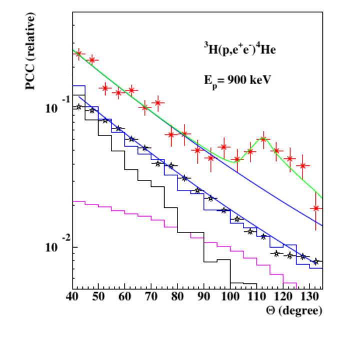
Beryllium (2016):

$$^{7}\text{Li} + p \to {}^{8}\text{Be}^{*} \to {}^{8}\text{Be} + \gamma \to {}^{8}\text{Be} + e^{+}e^{-} \qquad (1^{+} \to 0^{+})$$

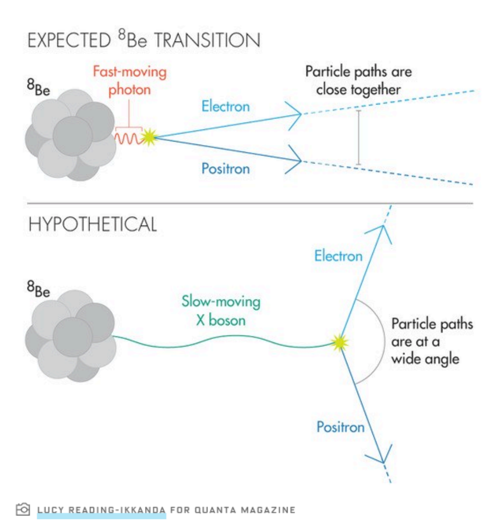
Helium (2019):

$$^{3}\text{H} + p \to {}^{4}\text{He}^{*} \to {}^{4}\text{He} + \gamma \to {}^{4}\text{He} + e^{+}e^{-} \qquad (0^{-} \to 0^{+})$$

From arXiv:1910.10459:



# Caricature




Mass of new particle: about 17 MeV.

# X17 Lagrangian

Vector or pseudoscalar?
Vector hypothesis (Jonathan Feng's group, PRL, 2016):

$$\mathcal{L}_{X,V} = -\sum_f \hbar'_f \, \bar{\psi}_f \, \gamma^\mu \, \psi_f X_\mu - \sum_N \hbar'_N \, \bar{\psi}_N \, \gamma^\mu \, \psi_N X_\mu \,,$$

Parameterization:

$$\hbar'_f = \varepsilon_f \, e \,, \qquad \hbar'_N = \varepsilon_N \, e \,,$$
$$\varepsilon_p = 2\varepsilon_u + \varepsilon_d \,, \qquad \varepsilon_n = \varepsilon_u + 2\varepsilon_d \,.$$

Available parameter space (electron, neutron, proton):

$$2 \times 10^{-4} < \varepsilon_e < 1.4 \times 10^{-3} \,,$$
$$|\varepsilon_n| = |\varepsilon_u + 2\varepsilon_d| \approx \left| \frac{3}{2} \, \varepsilon_d \right| \approx \frac{1}{100} \,,$$
$$|\varepsilon_p| = |2\varepsilon_u + \varepsilon_d| \lesssim 8 \times 10^{-4} \,.$$

Second equation ("conjecture"): we need this coupling in order to explain the ATOMKI experimental results!
Latter bound: we assume a "protophobic" interaction!

# X17 Lagrangian

Pseudoscalar hypothesis (Ellwanger and Moretti, JHEP, 2016):

$$\mathcal{L}_{X,A} = -\sum_f \hbar_f \,\bar{\psi}_f \,\mathrm{i}\gamma^5 \,\psi_f \,A - \sum_N \hbar_N \,\bar{\psi}_N \,\mathrm{i}\gamma^5 \,\psi_N \,A\,.$$

Parameterization:

$$\hbar_f = \xi_f \,\frac{m_f}{v}\,, \qquad \hbar_N = \xi_N \,\frac{m_N}{v}\,.$$

Ellwanger and Moretti obtain:

$$\hbar_p = \frac{m_p}{v}\,(-0.40\,\xi_u - 1.71\,\xi_d) \approx -2.4 \times 10^{-3}\,,$$
$$\hbar_n = \frac{m_n}{v}\,(-0.40\,\xi_u + 0.85\,\xi_d) \approx 5.1 \times 10^{-4}\,.$$

Available parameter space (electron):

$$4 < \xi_e < 500\,,$$
$$8.13 \times 10^{-6} < \hbar_e < 10^{-3}\,.$$

# Precision Atomic Physics I

For decades, atomic physicists have tried to push the accuracy of experiments and theoretical predictions of transitions in simple atomic systems higher [see Ted Hänsch's Nobel lecture]. The accurate measurements have led to stringent limits on the time variation of fundamental constants [see recent papers from MPQ, PTB, as well as the National Physical Laboratory (UK)] and enabled us to determine a number of important fundamental physical constants with unprecedented accuracy. Yet, a third motivation, hitherto not crowned with success, has been the quest to find signs of a possible low-energy extension of the Standard Model, based on a deviation of experimental results and theoretical predictions.

# Precision Atomic Physics II

Example:

PRL **95,** 163003 (2005) PHYSICAL REVIEW LETTERS week ending 14 OCTOBER 2005

TABLE I. Transition frequencies in hydrogen $\nu_{\mathrm{H}}$ and in deuterium $\nu_{\mathrm{D}}$ used in the 2002 CODATA least-squares adjustment of the values of the fundamental constants and the calculated values. Hyperfine effects are not included in these values.

| Experiment | Frequency interval(s) | Reported value $\nu$/kHz | Calculated value $\nu$/kHz |
|---|---|---|---|
| Niering *et al.* [1] | $\nu_{\mathrm{H}}(1S_{1/2}-2S_{1/2})$ | 2 466 061 413 187.103(46) | 2 466 061 413 187.103(46) |
| Weitz *et al.* [2] | $\nu_{\mathrm{H}}(2S_{1/2}-4S_{1/2})-\frac{1}{4}\nu_{\mathrm{H}}(1S_{1/2}-2S_{1/2})$ | 4 797 338(10) | 4 797 331.8(2.0) |
| | $\nu_{\mathrm{H}}(2S_{1/2}-4D_{5/2})-\frac{1}{4}\nu_{\mathrm{H}}(1S_{1/2}-2S_{1/2})$ | 6 490 144(24) | 6 490 129.9(1.7) |
| | $\nu_{\mathrm{D}}(2S_{1/2}-4S_{1/2})-\frac{1}{4}\nu_{\mathrm{D}}(1S_{1/2}-2S_{1/2})$ | 4 801 693(20) | 4 801 710.2(2.0) |
| | $\nu_{\mathrm{D}}(2S_{1/2}-4D_{5/2})-\frac{1}{4}\nu_{\mathrm{D}}(1S_{1/2}-2S_{1/2})$ | 6 494 841(41) | 6 494 831.5(1.7) |
| Huber *et al.* [3] | $\nu_{\mathrm{D}}(1S_{1/2}-2S_{1/2})-\nu_{\mathrm{H}}(1S_{1/2}-2S_{1/2})$ | 670 994 334.64(15) | 670 994 334.64(15) |
| de Beauvoir *et al.* [4] | $\nu_{\mathrm{H}}(2S_{1/2}-8S_{1/2})$ | 770 649 350 012.0(8.6) | 770 649 350 016.1(2.8) |
| | $\nu_{\mathrm{H}}(2S_{1/2}-8D_{3/2})$ | 770 649 504 450.0(8.3) | 770 649 504 449.1(2.8) |
| | $\nu_{\mathrm{H}}(2S_{1/2}-8D_{5/2})$ | 770 649 561 584.2(6.4) | 770 649 561 578.2(2.8) |
| | $\nu_{\mathrm{D}}(2S_{1/2}-8S_{1/2})$ | 770 859 041 245.7(6.9) | 770 859 041 242.6(2.8) |
| | $\nu_{\mathrm{D}}(2S_{1/2}-8D_{3/2})$ | 770 859 195 701.8(6.3) | 770 859 195 700.3(2.8) |
| | $\nu_{\mathrm{D}}(2S_{1/2}-8D_{5/2})$ | 770 859 252 849.5(5.9) | 770 859 252 845.1(2.8) |
| Schwob *et al.* [5] | $\nu_{\mathrm{H}}(2S_{1/2}-12D_{3/2})$ | 799 191 710 472.7(9.4) | 799 191 710 481.9(3.0) |
| | $\nu_{\mathrm{H}}(2S_{1/2}-12D_{5/2})$ | 799 191 727 403.7(7.0) | 799 191 727 409.1(3.0) |
| | $\nu_{\mathrm{D}}(2S_{1/2}-12D_{3/2})$ | 799 409 168 038.0(8.6) | 799 409 168 041.7(3.0) |
| | $\nu_{\mathrm{D}}(2S_{1/2}-12D_{5/2})$ | 799 409 184 966.8(6.8) | 799 409 184 973.4(3.0) |
| Bourzeix *et al.* [6] | $\nu_{\mathrm{H}}(2S_{1/2}-6S_{1/2})-\frac{1}{4}\nu_{\mathrm{H}}(1S_{1/2}-3S_{1/2})$ | 4 197 604(21) | 4 197 600.3(2.2) |
| | $\nu_{\mathrm{H}}(2S_{1/2}-6D_{5/2})-\frac{1}{4}\nu_{\mathrm{H}}(1S_{1/2}-3S_{1/2})$ | 4 699 099(10) | 4 699 105.4(2.2) |
| Berkeland *et al.* [7] | $\nu_{\mathrm{H}}(2S_{1/2}-4P_{1/2})-\frac{1}{4}\nu_{\mathrm{H}}(1S_{1/2}-2S_{1/2})$ | 4 664 269(15) | 4 664 254.3(1.7) |
| | $\nu_{\mathrm{H}}(2S_{1/2}-4P_{3/2})-\frac{1}{4}\nu_{\mathrm{H}}(1S_{1/2}-2S_{1/2})$ | 6 035 373(10) | 6 035 384.1(1.7) |
| Hagley and Pipkin [8] | $\nu_{\mathrm{H}}(2S_{1/2}-2P_{3/2})$ | 9 911 200(12) | 9 911 197.6(2.4) |
| Lundeen and Pipkin [9] | $\nu_{\mathrm{H}}(2P_{1/2}-2S_{1/2})$ | 1 057 845.0(9.0) | 1 057 844.0(2.4) |
| Newton *et al.* [10] | $\nu_{\mathrm{H}}(2P_{1/2}-2S_{1/2})$ | 1 057 862(20) | 1 057 844.0(2.4) |

In [Phys. Rev. A **97**, 042502 (2018)], we analyzed possibilities to detect the X17 in Lamb shift effects.

Unfortunately, it is incredibly hard to detect in the Lamb shift, in both electronic as well as muonic bound systems.

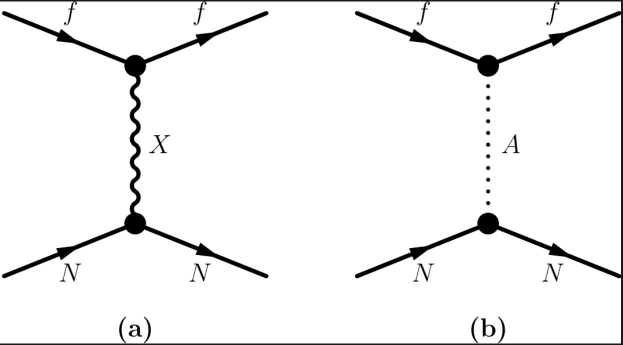
The mass range of 17 MeV with a reduced Compton wavelength of 11.8 fm is just too large (or, the Yukawa range of the potential too short) to lead to any effects which could be conclusively distinguished from the nuclear size effect.

Conclusion: Perhaps, perhaps, one might see the X17 in some weighted combination of transitions among excited states of muonic carbon.

Idea: Look at *hyperfine effects!*

# Research Program

Calculate the one-quantum exchange processes→
Obtain the effective Hamiltonians→
Look for suitable atomic systems for a detection



# Effective Hamiltonian for the Vector Case

Vector exchange leads to the following contribution to HFS:

$$H_{\mathrm{HFS},V} = \frac{\hbar'_f\,\hbar'_N}{16\,\pi\,m_f\,m_N}\Bigg[-\frac{8\pi}{3}\delta^{(3)}(\vec{r})\,\vec{\sigma}_f\cdot\vec{\sigma}_N - \frac{m_X^2\,\left(\vec{\sigma}_f\cdot\vec{r}\,\vec{\sigma}_N\cdot\vec{r}-r^2\,\vec{\sigma}_f\cdot\vec{\sigma}_N\right)}{r^3}\,\mathrm{e}^{-m_X\,r} - (1+m_X\,r)\,\frac{3\,\vec{\sigma}_f\cdot\vec{r}\,\vec{\sigma}_N\cdot\vec{r}-r^2\,\vec{\sigma}_f\cdot\vec{\sigma}_N}{r^5}\,\mathrm{e}^{-m_X\,r} - \left(2+\frac{m_f}{m_N}\right)\,(1+m_X\,r)\,\frac{\vec{\sigma}_N\cdot\vec{L}}{r^3}\mathrm{e}^{-m_X\,r}\Bigg]\,.$$

Derivation:
[Phys. Rev. A **101**, 062503 (2020)]

# Effective Hamiltonian for the Pseudoscalar Case

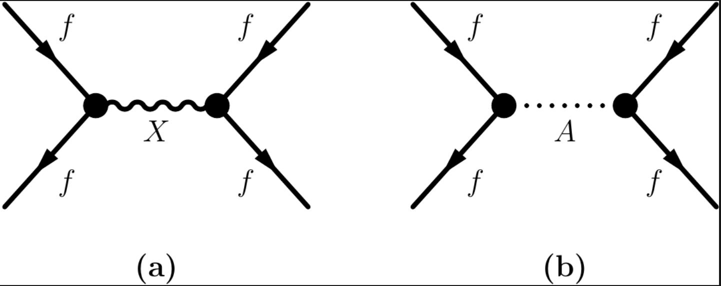
Pseudoscalar exchange exclusively contributes to the HFS:

$$H_{\mathrm{HFS},A} = \frac{h_f\, h_N}{16\,\pi\, m_f\, m_N} \left[ \frac{4\pi}{3} \delta^{(3)}(\vec{r})\, \vec{\sigma}_f \cdot \vec{\sigma}_N - \frac{m_X^2\, \vec{\sigma}_f \cdot \vec{r}\, \vec{\sigma}_N \cdot \vec{r}}{r^3}\, \mathrm{e}^{-m_X\, r} + (1 + m_X\, r)\, \frac{3\, \vec{\sigma}_f \cdot \vec{r}\, \vec{\sigma}_N \cdot \vec{r} - \vec{\sigma}_f \cdot \vec{\sigma}_N\, r^2}{r^5}\, \mathrm{e}^{-m_X\, r} \right].$$

Leaves Lamb shift invariant!
[Phys. Rev. A **101**, 062503 (2020)]

# Virtual Annihilation

Only for bound systems consisting of identical particles!
(a) vector hypothesis
(b) pseudoscalar hypothesis



# Virtual Annihilation Hamiltonian

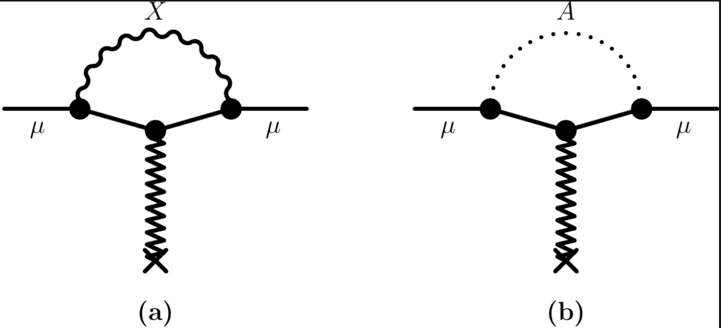
Virtual annihilation to a vector X17 (only contributes to hyperfine triplet states):

$$H_{\mathrm{ANN},V} = \frac{(h'_f)^2}{8(m_f^2 - \frac{1}{4}m_X^2)} \left(\vec{\sigma}_f \cdot \vec{\sigma}_{\overline{f}} + 3\right) \delta^{(3)}(\vec{r})\,.$$

Virtual annihilation to a pseudoscalar X17 (only contributes to hyperfine singlet states):

$$H_{\mathrm{ANN},A} = \frac{3h_f^2}{8(m_f^2 - \frac{1}{4}m_X^2)} \left(\vec{\sigma}_f \cdot \vec{\sigma}_{\overline{f}} - 1\right) \delta^{(3)}(\vec{r})\,.$$

# Bound on the Muon Coupling Parameter




Vector model:

$$\hbar'_\mu = (\hbar'_\mu)_{\rm opt} = 5.6 \times 10^{-4}\,.$$

Pseudoscalar model:

$$\hbar_\mu = (\hbar_\mu)_{\max} = 3.8 \times 10^{-4}\,.$$

# Enhancement of X17 Effects in Muonic Systems

Example: Relative correction to the $S$ state splitting is

$$\frac{E_{X,V}(nS_{1/2})}{E_F(nS_{1/2})} \approx -\frac{2h'_f h'_N}{g_N \pi} \frac{Z\, m_r}{m_X},$$
$$\frac{E_{X,A}(nS_{1/2})}{E_F(nS_{1/2})} \approx \frac{h_f h_N}{g_N \pi} \frac{Z\, m_r}{m_X}.$$

Have the reduced mass $m_r$ in the numerator after dividing by the leading-order Fermi splitting.
(Electronic systems: relative corrections to HFS of order $10^{-9}$.)
(So: Concentrate on muonic systems)

## Predictions for Muonic Deuterium

$S$ states (with realistic estimates for coupling parameters):

$$\frac{E_{X,V}^{(\mu d)}(nS_{1/2})}{E_F(nS_{1/2})} \doteq 3.8 \times 10^{-6}\,,$$
$$\frac{E_{X,A}^{(\mu d)}(nS_{1/2})}{E_F(nS_{1/2})} \doteq -1.0 \times 10^{-6}\,.$$

$P$ states:

$$\frac{E_{X,V}^{(\mu d)}(nP_{1/2})}{E_F(nP_{1/2})} \doteq 2.5 \times 10^{-7} \left(1 - \frac{1}{n^2}\right)\,,$$
$$\frac{E_{X,A}^{(\mu d)}(nP_{1/2})}{E_F(nP_{1/2})} \doteq 6.6 \times 10^{-8} \left(1 - \frac{1}{n^2}\right)\,.$$

This could be measurable but an enhanced understanding of nuclear polarization effects might be required for $S$ states.
For $P$ states, nuclear effects are strongly suppressed.

# Predictions for True Muonium $(\mu^+\mu^-)$

Define

$$\chi_V(nS) = \frac{4}{7}\frac{E_{X,V}(nS)}{E_F(nS)} + \frac{3}{7}\frac{E_{\mathrm{ANN},V}(nS)}{E_{\mathrm{ANN},\gamma}(nS)}\,,$$

$$\chi_A(nS) = \frac{4}{7}\frac{E_{X,A}(nS)}{E_F(nS)} + \frac{3}{7}\frac{E_{\mathrm{ANN},A}(nS)}{E_{\mathrm{ANN},\gamma}(nS)}\,.$$

Obtain the estimates

$$\chi_V(nS) \doteq\approx\ 1.3 \times 10^{-6}\,,$$

$$\chi_A(nS) \doteq\approx\ 2.1 \times 10^{-6}\,.$$

This could very well be measurable; only a very moderate improvement of the accuracy of the predictions for hadronic vacuum polarization is required.

# Conclusions

- X17 effects have to be confirmed in other nuclear transitions.
- Somewhat unfortunate energy range for atomic physics.
- Drastic enhancement of X17 effects in muonic systems.
- Look at the hyperfine splitting.
- Pseudoscalar hypothesis leads to "wrong sign" in regard to a muon $g-2$ "remedy".
- Estimates for X17-mediated effects for a number of atomic systems: [Phys. Rev. A **101**, 062503 (2020)].
- Most promising candidates: Muonic deuterium and true muonium.