EVIDENCE FOR A PROTOPHOBIC FIFTH FORCE

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Based on 1604.07411, “Evidence for a Protophobic Fifth Force From $^8$Be Nuclear Transitions,” and work in progress
MOTIVATIONS FOR A FIFTH FORCE

FORCE UNIFICATION

• The quantum numbers of SM matter fields are explained by GUTs:
  $SU(3) \times SU(2) \times U(1) \rightarrow SU(5), SO(10), E6, E8, \ldots$

• $SO(10) \ldots \rightarrow 5\text{th force}$

DARK MATTER

• Dark sector: new matter and new forces

• Mediator $\rightarrow$ weakly-coupled 5$\text{th}$ force

These beautiful ideas have focused a great deal attention on the search for a fifth force: $Z'$ bosons, dark photons, dark $Z$'s, and general light, weakly-coupled particles
Observation of Anomalous Internal Pair Creation in $^8$Be: A Possible Indication of a Light, Neutral Boson


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Electron-positron angular correlations were measured for the isovector magnetic dipole 17.6 MeV ($J^p = 1^+, T = 1$) state → ground state ($J^p = 0^+, T = 0$) and the isoscalar magnetic dipole 18.15 MeV ($J^p = 1^+, T = 0$) 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 $16.70 \pm 0.35 \text{ (stat)} \pm 0.5 \text{ (syst)} \text{ MeV}/c^2$ and $J^p = 1^+$ was created.
• $^8\text{Be}$: 4 protons + 4 neutrons
• Perhaps best known for its supporting role in $\alpha + \alpha + \alpha \rightarrow ^{12}\text{C}$
• The entire $^8\text{Be}$ spectrum is well studied

THE $^8$BE EXPERIMENT AT MTA ATOMKI

- 1 $\mu$A proton beam hits thin $^7$Li targets
- $E_p = 1.025$ MeV $\rightarrow$ $^8$Be* resonance, which then decays:
  - Hadronic: $B(p^7$Li) $\approx 100\%$
  - Electromagnetic: $B(^8$Be $\gamma) \approx 1.5 \times 10^{-5}$
  - Internal Pair Conversion: $B(^8$Be $e^+ e^-) \approx 5.5 \times 10^{-8}$
• Measure the $e^+e^-$ opening angle $\theta$ and invariant mass
• Background fluctuation probability: $5.6 \times 10^{-12}$ ($6.8\sigma$)
• Best fit to new particle: $\chi^2$/dof = 1.07
  
  $m = 16.7 \pm 0.35$ (stat) $\pm 0.5$ (sys) MeV
  
  $B(^8\text{Be}^* \rightarrow ^8\text{Be} X) / B(^8\text{Be}^* \rightarrow ^8\text{Be} \gamma) = 5.6 \times 10^{-6}$
SIGNAL CHARACTERISTICS

• The excess is not a “last bin” effect: bump, not smooth excess

• In scan through $p$ resonance energy, excess rises and falls

• Peaks in opening angle $\theta$ and invariant mass correspond; required for particle interpretation, not for all backgrounds

• LiF$_2$, LiO$_2$ target “impurities” understood, do not lead to such energetic photon and IPC events

• Comparable excess not seen for 17.64 MeV state; explainable by phase-space suppression for 17 MeV state

• Completely different from previous claims of excesses: different experiment, different collaboration, different claimed mass, extraordinary statistics, and a bump, not smooth excess
OPEN QUESTIONS

• What kinds of neutral bosons are possible?

• What are the required parton-level couplings?

• Is this consistent with all other experiments?

• Is there a UV-complete model that predicts this?

• What other experiments can check this?
**SPIN 0 NEUTRAL BOSONS**

**SCALARS**

"DARK HIGGS"

- $J^P$ Assignments: $1^+ \rightarrow 0^+ 0^+ $
- L Conservation: $L = 1$
- Parity Conservation: $P = (-1)^L = 1$
- Forbidden in parity-conserving theories

**PSEUDOSCALARS**

"AXION-LIKE PARTICLES"

- Forbidden for large range of $a_{\gamma\gamma}$ couplings

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**Figure 1**

Summary of constraints on the ALP parameter space (compilation from [11] and references therein; in particular SLAC electron fixed target limits are from [4, 9, 18]). The new limits from the proton beam dump experiments CHARM and NuCal, derived in the present paper, are shown in turquoise and orange.

The ALP lifetime is given by $\tau = \frac{1}{g_{a\gamma}^2 m_a}$. For an ALP with energy $E_a$ in the laboratory frame, the typical decay length is then given by $l_a = \tau \pi \frac{64}{\pi} \frac{1}{E_a g_{a\gamma}^2 m_a^4} \frac{1}{m_a}$, typically on the order of $10^{-8}$ GeV.

Both smaller couplings and smaller ALP masses are in fact very strongly constrained by astrophysical and cosmological observations. Larger couplings, on the other hand, can be tested directly at colliders such as LEP or the LHC [11].
VECTORS: SPIN-1 GAUGE BOSONS

• What quark-, nucleon-level couplings are required? In general requires calculating nuclear matrix elements

• But for 1\textsuperscript{-} vector, in the EFT, there is only 1 operator
  \[ \frac{1}{\Lambda} \epsilon_{\mu\nu\alpha\beta} \left( \partial_\mu ^8\text{Be}^*_\nu - \partial_\nu ^8\text{Be}^*_\mu \right) X_\alpha \beta ^8\text{Be} \]

• The width is
  \[ \Gamma(^8\text{Be}^* \to ^8\text{Be} X) = \frac{(e/2)^2(\varepsilon_p + \varepsilon_n)^2}{3\pi\Lambda^2} |\mathcal{M}|^2 |\vec{p}_X|^3 \]

• The nuclear matrix elements and \( \Lambda \) cancel in the ratio
  \[ \frac{B(^8\text{Be}^* \to ^8\text{Be} X)}{B(^8\text{Be}^* \to ^8\text{Be} \gamma)} = (\varepsilon_p + \varepsilon_n)^2 \frac{|\vec{p}_X|^3}{|\vec{p}_\gamma|^3} \approx 5.6 \times 10^{-6} \]

  where \( \varepsilon_p = 2\varepsilon_u + \varepsilon_d \) and \( \varepsilon_n = \varepsilon_u + 2\varepsilon_d \) are the nucleon X-charges (in units of e)
THE REQUIRED PARTON-LEVEL COUPLINGS

• To get the right signal strength:

$$|\varepsilon_u + \varepsilon_d| \approx 3.7 \times 10^{-3}$$

• To decay within 1 cm:

$$|\varepsilon_e| \gtrsim 1.3 \times 10^{-5}$$

• This cannot be a dark photon
• The dominant constraints are null results from searches for $\pi^0 \rightarrow X \gamma \rightarrow e^+ e^- \gamma$

\[
\pi^0 \xrightarrow{\gamma} u, d \quad \frac{1}{\sqrt{2}} (u\bar{u} - d\bar{d})
\]

• Eliminated if $Q_u X_u - Q_d X_d \approx 0$ or $2X_u + X_d \approx 0$ or $X_p \approx 0$

• A protophobic gauge boson with couplings to neutrons, but suppressed couplings to protons, can explain the $^8$Be signal without violating other constraints
• Consider all constraints and also the region favored by \((g-2)\mu\).
• In the end, require \(\varepsilon_u, \varepsilon_d \sim \text{few } 10^{-3}\) with \(~10\%\) cancelation for protophobia, \(10^{-4} < \varepsilon_e < 10^{-3}\), and \(|\varepsilon_e \varepsilon_\nu|^{1/2} < 3 \times 10^{-4}\).
• Gauge the $U(1)_{B-L}$ global symmetry of the SM
• This is anomaly-free with the addition of 3 sterile neutrinos
• Generically the B-L boson mixes with the photon:
  \[ \begin{align*}
  \varepsilon_u & : \frac{2}{3} \varepsilon + \frac{1}{3} \varepsilon_{B-L} \\
  \varepsilon_d & : \frac{-1}{3} \varepsilon + \frac{1}{3} \varepsilon_{B-L} \\
  \varepsilon_{\nu} & : -\varepsilon_{B-L} \\
  \varepsilon_{e} & : -\varepsilon - \varepsilon_{B-L} 
  \end{align*} \]
• For $\varepsilon + \varepsilon_{B-L} \approx 0$, we get both $\varepsilon_u \approx \varepsilon/3$ and $\varepsilon_d \approx -2\varepsilon/3$ (protophobia) and $\varepsilon_{e} \ll \varepsilon_{u,d}$!
• The neutrino X-charge can be suppressed in a number of ways, e.g., by mixing with X-charged sterile neutrinos
FUTURE TESTS: NUCLEAR PHYSICS

- The most direct test would be to look for other nuclear IPC transitions.

- The $^8$Be 18.15 and 17.64 transitions are the largest known with discrete gamma rays.

- Would likely need to re-examine the $^8$Be 18.15 transition.
FUTURE TESTS: “DARK PHOTON” EXPTS

- Also KLOE-2, SHiP, SeaQuest, PADME, …
CONCLUSIONS

• The 6.8σ $^8$Be IPC signal currently has no known experimental or nuclear physics explanations

• Particle interpretation yields a $\chi^2$/dof = 1.07 best fit with
  $$m = 16.7 \pm 0.35 \text{ (stat)} \pm 0.5 \text{ (sys)} \text{ MeV}$$
  $$\frac{B(^8\text{Be}^* \to ^8\text{Be} X)}{B(^8\text{Be}^* \to ^8\text{Be} \gamma)} = 5.6 \times 10^{-6}$$

• The data are consistent with a protophobic gauge boson that mediates a 5th force with range 12 fm, milli-charged couplings to quarks and leptons, and explains $(g-2)_\mu$

• A UV-complete, anomaly-free model: B-L gauge boson that kinetically mixes with the photon, with active $\nu$ mixing with X-charged sterile neutrinos

• Many upcoming experimental tests