Non-accelerator probes of light bosons
The $^8\mathrm{Be}$ anomaly & a Protophobic 5^{th}-force

Iftah Galon

University of California, Irvine

March 23, 2017

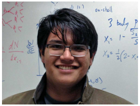
Collboration


Jonathan Feng

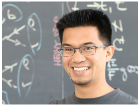

Bart Fornal


Iftah Galon


Susan Gardner


Jordan Smolinsky


Tim Tait


Flip Tanedo

based on

- Phys.Rev.Lett. 117 (2016) no.7, 071803 ,arXiv:1604.07411
- Phys.Rev. D95 (2017) no.3, 035017, arXiv:1608.03591

Motivation - Complementarity

New Forces:

- Dark Matter $\subset$ Dark sectors
- GUTs & EWSB
- ν's and $B - L$
- light weakly coupled NP

$\Longrightarrow$

New Forces

light bosons

Complementary to colliders $\Rightarrow$ Low-Energy

Hints ?

- $(g-2)_\mu$
- Proton radius talk by Richard Hill
- KTeV: $\pi^0 \to e^+e^-$

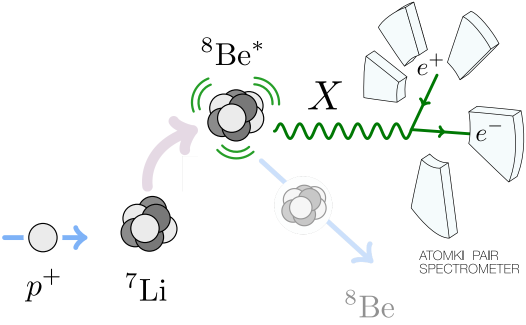
MeV-scale: Nuclear Physics

Treiman, Wilczek (1978)
Donnelly, Freedman, Lytel, Peccei, Schwartz (1978)
Savage, McKeown, Filippone, Mitchell (1986)

Khan Schmitt & Tait, arXiv:0712.0007
Khan Krnjaic, & Tait, arXiv:1609.09072

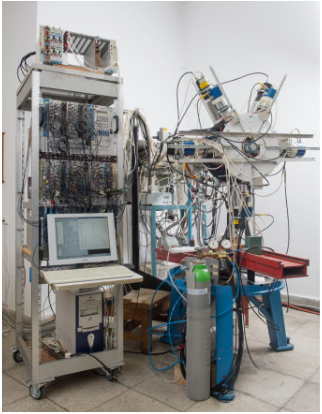
The Atomki Experiment

Schematics



by F. Tanedo

Experiment



Gulyás et al; NIM A808, 2016, 21-26

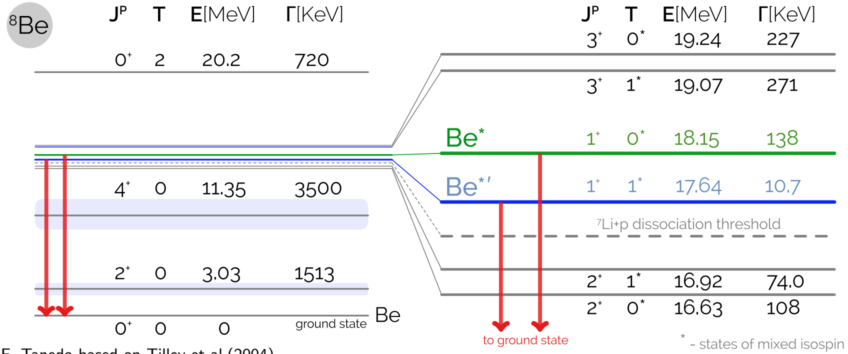
Nuclear Reaction: $p^+ + {}^7\mathrm{Li} \rightarrow {}^8\mathrm{Be}^*$

$\Delta E_p \sim 10\mathrm{keV}$, $\Delta\theta_{ee} \sim 2^\circ$ (design)

EM transition: ${}^8\mathrm{Be}^* \rightarrow \mathrm{e}^+\mathrm{e}^- + {}^8\mathrm{Be}$

Nuclear Structure of $^8\mathrm{Be}$

$^8\mathrm{Be}$: one of the largest γ emission of all nuclei



by F. Tanedo based on Tilley et al.(2004)

$^8\mathrm{Be}^*$ decays

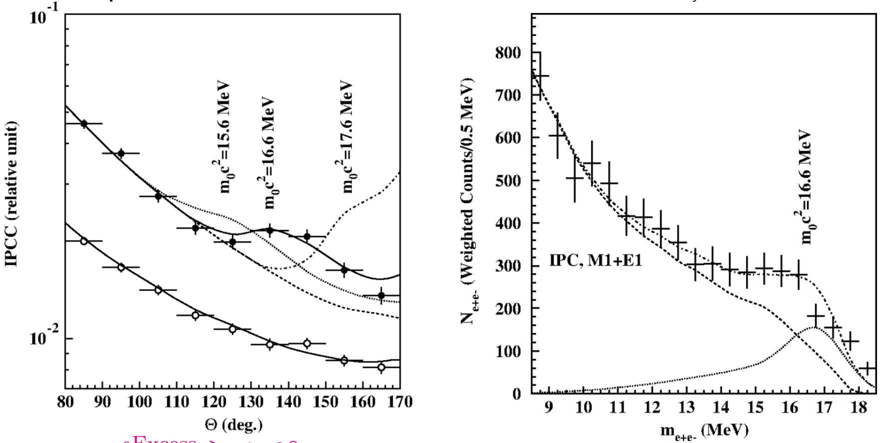
- $\mathrm{Br}(p^+ + {}^7\mathrm{Li}) \approx 100\%$
- $\mathrm{Br}({}^8\mathrm{Be} + \gamma) \approx 1.4 \times 10^{-5}$
- $\mathrm{Br}({}^8\mathrm{Be} + e^+e^-) \approx 3.9 \times 10^{-3}\ \mathrm{Br}({}^8\mathrm{Be} + \gamma)$

$^8\mathrm{Be}^*$ structure

- J^P doublets are T-admixtures
- $\mathcal{O}(20\ \mathrm{MeV})$ $E1$-states with large Γ

The Atomki Result

- Bump-like excess in two distributions from Krasznahorkay et al.



$\theta_{ee}^{\text{Excess}} \gtrsim 140^\circ$ $\quad$ $m_{ee} \approx 17\ \text{MeV}$

Excess statistical significance 6.8σ — $1.07\chi^2/\text{d.o.f}$

The Atomki Result

- bump, not smooth excess, not a "last bin" effect
- excess in θ_{ee} and m_{ee} agree
- $M1$: $18.15\ \mathrm{MeV}$ ✓ $17.64\ \mathrm{MeV}$ ✗
- checks:
  $|y < \frac{1}{2}|$, $E_{ee} > 18\ \mathrm{MeV}$, E_p-scan, $E1$-contam, bkgs
- Excess statistical significance 6.8σ — $1.07\chi^2/\mathrm{d.o.f}$ favors intermediate boson

Interpretations

- Nuclear Physics Theory - New Phenomena ? talk by Xilin Zhang
  $\Rightarrow$ Cannot account for $^{8}\mathrm{Be}$ signal Zhang & Miller arXiv:1703.04588 [nuc-th]

- Unknown Systematic Effect ?
  $\Rightarrow$ other nuclear transition fit predictions

- Today: New Physics $\Longrightarrow$ X-boson

can be verified in
upcoming & future experiments

The X-properties

- $m_X = 16.7 \pm 0.35(stat) \pm 0.5(sys)\ \mathrm{MeV}$
- $\frac{\Gamma\left({}^8\mathrm{Be}^* \to {}^8\mathrm{Be}+\mathrm{X}\right)}{\Gamma({}^8\mathrm{Be}^* \to {}^8\mathrm{Be}+\gamma)} = 5.8 \times 10^{-6}$ $\qquad \frac{\Gamma\left({}^8\mathrm{Be}^{*\prime} \to {}^8\mathrm{Be}+\mathrm{X}\right)}{\Gamma({}^8\mathrm{Be}^{*\prime} \to {}^8\mathrm{Be}+\gamma)} \approx 0$
- X must be an iso-scalar
- X is a boson, but is it a
  - Scalar, $J^\pi = 0^+$ forbidden by J^P conservation
  - Pseudo-Scalar, $J^\pi = 0^-$ Ellwanger & Morreti, arXiv:1609.01669
  - Vector, $J^\pi = 1^-$
  - Pseudo-Vector, $J^\pi = 1^+$ talk by Jonathan Kozaczuk

Scalar ?

Spin and Parity in the decay

$$J^{\pi}(^{8}\mathrm{Be}) = 0^{+} \quad \Longleftarrow \quad \mathrm{J}^{\pi}(^{8}\mathrm{Be}^{*}) = 1^{+} \quad \Longrightarrow \quad \mathrm{J}^{\pi}(\mathrm{X}) = 0^{+}$$

Total angular momentum conservation

$$J = L + S \longrightarrow L_{final} = 1$$

Then

$$P_{\mathrm{initial}} = (+) \neq (-) = (+)(+)(-)^{L=1} = P_{\mathrm{final}}$$

A Scalar is forbidden by parity

Vectors

Is X a Dark Photon, A', kinetically mixing with $U(1)_{EM}$

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{\epsilon}{2}F'^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu \implies \mathcal{L}_{int} \supset \epsilon A'_\mu J^\mu_{EM}$$

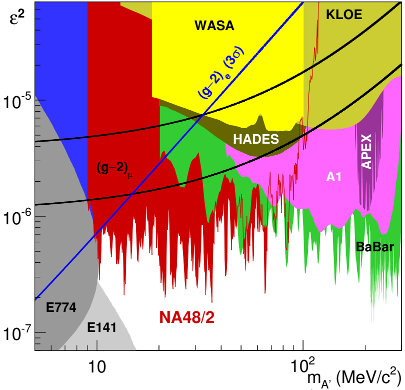
Holdom Phys. Lett. B166 (1986) 196

NA48/2 search for

$$\pi^0 \to \gamma(X \to e^+e^-):$$

$$\epsilon < (8-12)\times 10^{-4}$$

No account for $(g-2)_\mu$



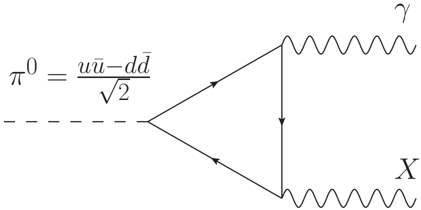
from NA48/2, arxiv:1504.00607

A Way Around $\Longrightarrow$ Protophobia

Assume

$$\mathcal{L}_{int} \supset X_\mu J^\mu_X \qquad J^\mu_X = e \sum_f \epsilon_f \, \bar{\psi}_f \gamma^\mu \psi_f$$

Main bound $\quad \Gamma\left(\pi^0 \to \gamma(X \to e^+ e^-)\right) \propto Tr\left(Q^{EM} Q^X\right)$



$$\mathrm{BR}(\pi^0 \to \gamma \mathrm{X}) \approx \frac{1}{9} \left(2\epsilon_\mathrm{u} + \epsilon_\mathrm{d}\right)^2$$

Disappears for

$$2\epsilon_u \approx -\epsilon_d \quad \Longrightarrow \quad \epsilon_\mathrm{p} = 0$$

Nuclear $\Longrightarrow$ Particle: EFT approach

Following Petrov and Blechman

$$\mathcal{L}_{int} \supset \sum \frac{\mathcal{O}_d}{\Lambda^{d-4}},$$

- $\mathcal{O}$s contain fields ${}^8\mathrm{Be}^*_\mu$, ${}^8\mathrm{Be}$, X_μ, A_μ, derivatives ∂_μ, and $\epsilon^{\mu\nu\rho\sigma}$
- $\mathcal{O}$s have definite spin & parity.
- expansion validity $\frac{r}{\lambda} \approx \frac{6\ \mathrm{MeV}}{100\ \mathrm{MeV}} \ll 1$
- $$\Gamma\left({}^8\mathrm{Be}^* \to\ {}^8\mathrm{Be}\ \mathrm{V}\right) = \frac{1}{3}\frac{|\vec{k}_V|}{8\pi m^2_{{}^8\mathrm{Be}^*}} |\langle {}^8\mathrm{Be}\ \mathrm{V}|\mathcal{L}_{\mathrm{int}}|{}^8\mathrm{Be}^*\rangle|^2_{\mathrm{spins}}$$

EFT $\Leftrightarrow$ Microscopic Theory: Vectors

$V = \gamma, \quad X$

EFT:

At LO, the single operator

$$\mathcal{L}^V_{int} = \frac{e\,\epsilon_V}{\Lambda_V}\; {}^8\mathrm{Be}\; \mathrm{G}_{\mu\nu}\; \mathrm{F}^{\mathrm{V}}_{\rho\sigma}\; \epsilon^{\mu\nu\rho\sigma}$$

with $G_{\mu\nu} = \partial^8_\mu \mathrm{Be}^*_\nu - \partial^8_\nu \mathrm{Be}^*_\mu$

Note, EOMs: $\begin{cases} \partial^\mu F_{\mu\nu} = 0 \\ \partial^\mu\ {}^8\mathrm{Be}^*_\mu = 0 \end{cases}$ Then

$$\Gamma_V \propto \frac{e^2 \epsilon_V^2}{\Lambda_V^2} |\vec{k}_X|^3$$

Microscopic:

$$\mathcal{L}_{int} \supset V_\mu J^\mu_V$$

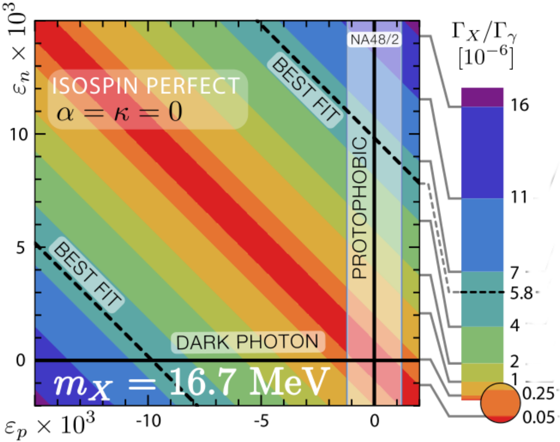
$$J^\mu_V = e \sum_f \epsilon_f \bar{\psi}_f \gamma^\mu \psi_f$$

decompose into: $J^\mu_0, \;\; J^\mu_1$

IsoSpin Conserving Scenario

Naively

- $^8\mathrm{Be}^*$: isosinglet
- $^8\mathrm{Be}^{*\prime}$: isovector
- $H_{\mathrm{int}}^{\mathrm{Nuc}}$ preserves isospin



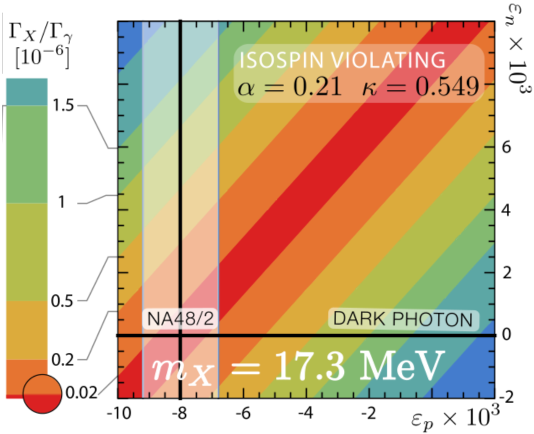
$$\frac{\Gamma_X}{\Gamma_\gamma} = (\epsilon_p + \epsilon_n)^2 \frac{|\vec{k}_X|^3}{|\vec{k}_\gamma|^3} = 5.8 \times 10^{-6}$$

$$\begin{cases} \epsilon_p + \epsilon_n = 0.01 \quad \text{or} \\ \epsilon_u + \epsilon_d = 3.3 \times 10^{-3} \end{cases}$$

IsoSpin Violating Scenario

In reality

- $^8\mathrm{Be}^*$ & $^8\mathrm{Be}^{*\prime}$: iso-admixes
- $H_{\mathrm{int}}^{\mathrm{Nuc}} \supset$ ~~isospin~~
- $m_X \gtrsim 17$ MeV $\Rightarrow$ lower rates
  (allow $\times 10$ smaller)



Nuclear Physics input:

Pastore et al.
Phys.Rev. C90 (2014) no.2, 024321

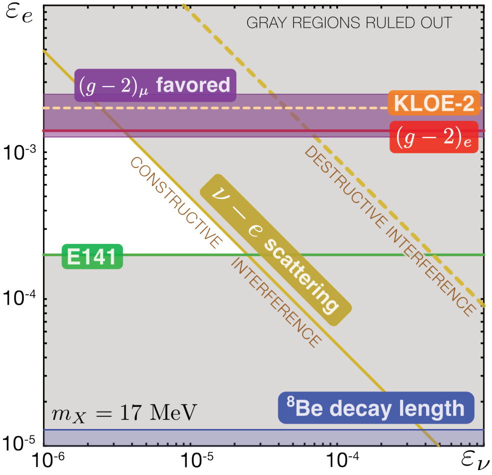
$$\begin{cases} \epsilon_n = (2 - 10) \times 10^{-3} < 2.5 \times 10^{-2} \\ \epsilon_p \leq 1.2 \times 10^{-3} \end{cases}$$

Barbieri & Ericson 1975
n-Pb scattering

Lepton Sector Constraints

At $m_X = 17$ MeV

- $(g-2)_e$
  $|\epsilon_e| < 1.4 \times 10^{-3}$
- KLOE2 $e^+e^- \to \gamma X, X \to e^+e^-$
  $|\epsilon_e| < 2 \times 10^{-3}$
- TEXONO: $\nu - e$ scat.
  $$\begin{cases} \sqrt{|\epsilon_e \epsilon_\nu|} < 7 \times 10^{-5} (const.) \\ \sqrt{|\epsilon_e \epsilon_\nu|} < 3 \times 10^{-4} (dest.) \end{cases}$$
- prompt decay ≤ 1 cm
  $|\epsilon_e| \geq 1.3 \times 10^{-5}$
- Beam dumps $\begin{cases} |\epsilon_e| > 2 \times 10^{-4} \\ |\epsilon_e| < 10^{-8} \end{cases}$



Model Building - The benchmark

$$\epsilon_n = \epsilon_u + 2\epsilon_d = (2 - 10) \times 10^{-3}$$

$$\epsilon_p = \epsilon_d + 2\epsilon_u < 1.2 \times 10^{-3}$$

$$2 \times 10^{-4} \leq |\epsilon_e| \leq 1.4 \times 10^{-3} \quad (g-2)_\mu \; explained$$

$$\sqrt{|\epsilon_e \epsilon_\nu|} < 7 \times 10^{-5} (const.)$$

$$\sqrt{|\epsilon_e \epsilon_\nu|} < 3 \times 10^{-4} (dest.)$$

Model Building

- gauge a global symmetry: $U(1)_B$, & kinetic mix. $\gamma - X$

$$\epsilon_\psi = \epsilon_B Q_\psi^B + \epsilon Q_\psi^{EM} \quad \Longrightarrow \quad \begin{cases} \epsilon_p = \epsilon_B + \epsilon \\ \epsilon_n = \epsilon_B \\ \epsilon_e = \epsilon_n - \epsilon_p \\ \epsilon_\nu = 0 \end{cases}$$

- $Q^{eff} \approx Q - B$ in the protophobic limit

- For $(\epsilon_p,\ \epsilon_n) \approx (0.001,\ 0.002)$ & $\epsilon_\mu \approx \epsilon_e$ partially accounts for $(g-2)_\mu$ with mild $\mathcal{O}(\%10)$ fine-tuning

- no ν coupling - strongest constraint, and no $X \to inv$

The $U(1)_B$ Model

- cancel anomalies: $\Longrightarrow$ Add matter

  Wise et. al (2013), Fileviez Perez et. al (2013, 2014), Duerr et.al (2015)

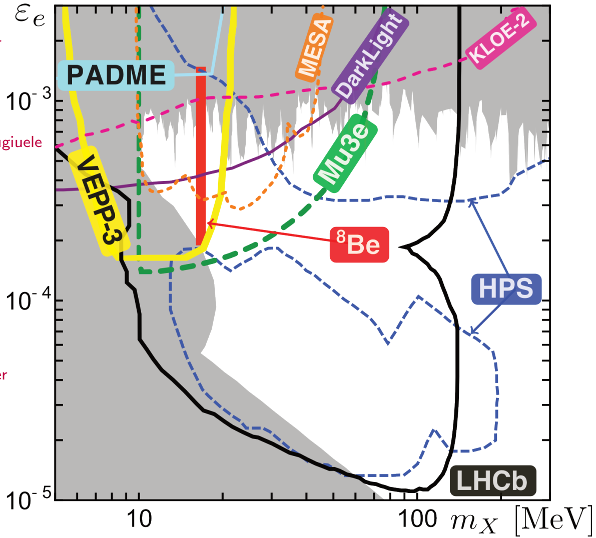
- Constraints: LHC & LEP, Oblique Params. , $h \to \gamma\gamma$ decays

- Prospects: B-charged vector-like set of "leptons" $\Rightarrow$ *DM*

- $U(1)_B$ SSB by $\langle S_B \rangle \approx 10\ \mathrm{GeV} \frac{0.002}{|\epsilon_B|}$ (unlike TeV models)

Promising Outlook to Verify/Exclude ^{8}Be result

- ^{10}B : 19.3 MeV
- ^{10}Be : 17.79 MeV
- ^{4}He > 23 MeV Leach & Brodeur
- ATOMKI - new detector
- talk by Raphael Lang
- Isotope shift - talk by Claudia Frugiuele
- PADME - talk by Mauro Raggi
- HPS - talk by Omar Moreno
- LHCb - talk by Philip Ilten
- SHIP talk by Antonia di Crescenzo
- SeaQuest talk by Ming Liu
- DarkLight talk by Michael Kohl
- MMAPS (vis) talk by J. Alexander
- TUNL (HIGS facility γ Nuc)
- UK VdG
- TREK@JPARC K^+ decays
- BESIII
- LHC - prob UV



Conclusions

- Big problems need solutions: Dark Matter (sector), GUT& EWSB, particle quantum numbers
- 6.8σ significance result ($1.07\ \chi^2/dof$) favors intermediate particle,
  a new boson X, at $m_X \approx 17\ \mathrm{MeV}$
- NOT a dark photon, but could easily emerge from DM & GUT considerations.
- could account for additional anomalies like $(g-2)_\mu$, KTEV
- upcoming and future experiment are sensitive to X, and to Dark Sector particles at the EW scale.

Thank You

Backup Slides

ATOMKI Setup

- Van de Graaff accelerator $\longrightarrow$ p^+ beam , resolution $\mathcal{O}(100 \text{ keV})$ $\longrightarrow$ generate known nuclear excited states on-resonance
- Relevant Nuclear Reactions

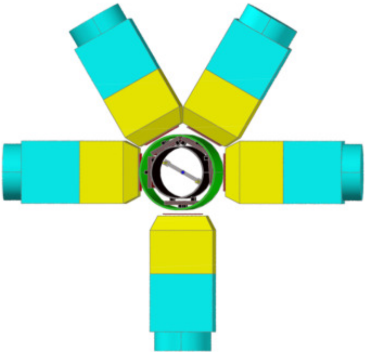
$$p^+ + {}^7\text{Li} \longrightarrow {}^8\text{Be}$$

-

$$\begin{aligned} E_p^{kin} &= 1.03 \text{ MeV} \longrightarrow {}^8\text{Be}^* \ (18.15 \text{ MeV}) \\ E_p^{kin} &= 0.441 \text{ MeV} \longrightarrow {}^8\text{Be}^{*\prime} \ (17.64 \text{ MeV}) \end{aligned}$$

ATOMKI Setup

- plastic scintillator $\Delta E - E$ setup, position using: MWPC
  - 5 Telescope circular array, high efficiency $\approx 7 \times 10^{-3}$
  - large θ_{ee} coverage
  - $max(E_{ee}) \approx 18$ MeV
  - $\Delta\theta = 2^\circ$ (design)
  - $\Delta\theta = 6^\circ$, beam position on target, calibration



from Gulyás et al; NIM A808, 2016, 21-26

New Boson, X, Interpretation

Why a new boson ? Why $m_X \approx 17$ MeV

- $P_X(m_X \approx 17 \text{ MeV}) = 6.35 \text{ MeV}$
- $\theta_{ee}^{min} = \text{ArcCos}\left(\frac{P_X^2 - m_X^2 + 4m_e^2}{P_X^2 - m_X^2 - 4m_e^2}\right) \approx 140^\circ$
- m_{ee} shows a bump at $m_{ee} \approx m_X$

Skepticism

A (non-exhaustive) list of reasons to doubt

- Background sources ? γs, Cosmic μs
- Nuclear interference effects
- Claims of various excess in $^8\mathrm{Be}$ in the past (de Boer et al.)
- The $\mathrm{Be}^{*\prime}$ state @ 17.64 MeV

Tackling Skepticism 1 - Backgrounds

Dealing with backgrounds

- γs - mainly from target area scattering (γ-conversion),
  - suppressed by target design
  - reject using coincidence requirements in detectors
  - the effect does not appear in the 17.64 MeV state
  - the effect does not appear off-resonance
- cosmic μs
  - shape estimated from off-time.
  - scale: comparing and $E_{ee} > 20\ \mathrm{MeV}$ during run to off-time
- Target composition LiF_2, LiO_2 known and understood

Tackling Skepticism 1 - Backgrounds

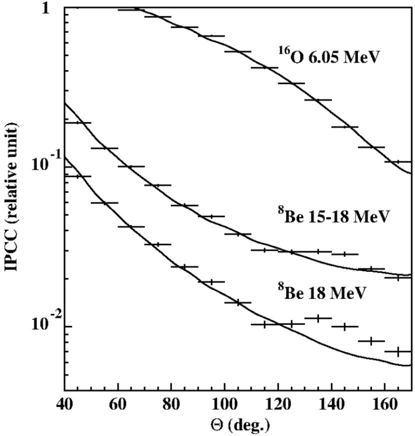
Verification and Cuts

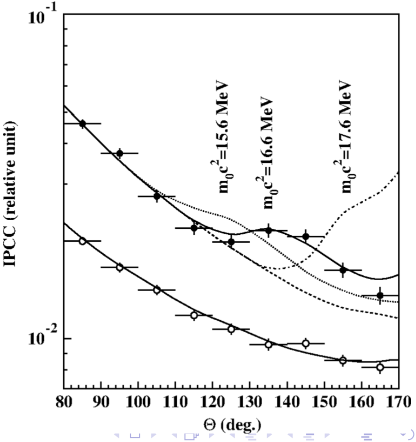
Gate threshold:

$E_{ee} \geq 18\ \mathrm{MeV}$

symmetric spectra:

$|y| = \left| \frac{E^{kin}_{e+} - E^{kin}_{e-}}{E^{kin}_{e+} + E^{kin}_{e-}} \right| \leq 0.5$

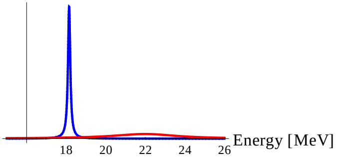




Tackling Skepticism 2 - Interference Effects

E1 - M1

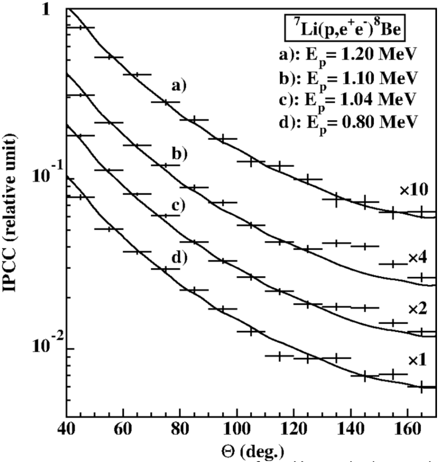
- Non-Resonant production



$M1 + 0.23E1$ composition

- known γ-FB-anisotropy can affect Θ_{ee}(detector position)

Mainsbridge, Nucl. Phys. 21, 1 (1960)
Zahnow, et al. Z. Phys. A 351, 229 (1995)
Goldring, Proc. Phys. Soc. 66, 341 (1953)



from Krasznahorkay et al.

Excess statistical significance 6.8σ at $E_p^{kin} = 1.1\ \mathrm{MeV}$

Tackling Skepticism 3 - Past Experience

Too many past excesses

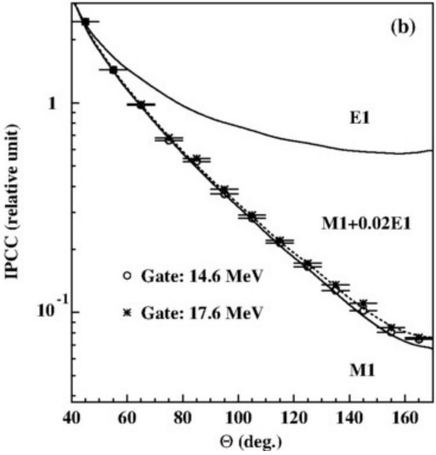
- de Boer et al.
  - 9 MeV in $M1$-transition in $^8\mathrm{Be}^{*\prime}$
  - 12 MeV boson in $M1$-transition in $^8\mathrm{Be}^{*\prime}$
  - $E1$-transition ^{12}C and
- Krasznahorkay et al.: 13 MeV

Persuasive Arguments

- Better angular acceptance - large θ_{ee} coverage
- Accounting for interference effects

Tackling Skepticism 4 - 17.64 MeV

The e^+e^- spectrum of the $^8\mathrm{Be}^{*\prime}$ does not exhibit an excess



from Krasznahorkay et al.

Matches $M1 + 0.02E1$ composition (and excludes past excess claims)

Tackling Skepticism 4 - 17.64 MeV

- Angular systematic error $\Delta\theta = 6^\circ \to \Delta m_{syst} = 0.5$
  In total

$$m_X = (16.7 \pm 0.35(stat) \pm 0.5(syst))\ \mathrm{MeV}$$

Consistent with $m_X = 17.55\ \mathrm{MeV}$ at 1σ

Phase-Space suppressed decay

Rates

Comparing γ & X: $\epsilon_\gamma = 1$

$$\frac{\Gamma\left({}^8\mathrm{Be}^* \to {}^8\mathrm{Be} + \mathrm{X}\right)}{\Gamma\left({}^8\mathrm{Be}^* \to {}^8\mathrm{Be} + \gamma\right)} = \epsilon_X^2 \, \frac{\Lambda_X^2}{\Lambda_\gamma^2} \, \frac{|\vec{k}_X|^3}{|\vec{k}_\gamma|^3} = 5.8 \times 10^{-6}$$

But what are the Λs ?

Compare known results

$$\Gamma\left({}^8\mathrm{Be} \to {}^8\mathrm{Be} + \gamma\right) \Longrightarrow \Lambda_\gamma \approx 2\ \mathrm{GeV}$$

But how to disentangle ϵ_X and Λ_X

Currents and Amplitudes

Conserved isospin limit $\Longrightarrow$ isospin doublet

$$N = \begin{pmatrix} p \\ n \end{pmatrix}$$

The isosinglet and isovector currents are

$$J_0^\mu = \bar{N}\gamma^\mu N = J_p^\mu + J_n^\mu \qquad J_1^\mu = \bar{N}\gamma^\mu T^3 N = J_p^\mu - J_n^\mu$$

The EM current is

$$J_{EM} = eJ_p^\mu = \frac{e}{2}(J_0^\mu + J_1^\mu)$$

while X couples to

$$\begin{aligned} J_X^\mu &= e_{EM}\ \epsilon_p\ J_p^\mu \ + e_{EM}\ \epsilon_n J_n^\mu \\ &= \frac{e_{EM}}{2}(\epsilon_p + \epsilon_n)J_0^\mu + \frac{e_{EM}}{2}(\epsilon_p - \epsilon_n)J_1^\mu \end{aligned}$$

Currents and Amplitudes

So that

$$\begin{aligned}\langle {}^8\mathrm{Be}|\mathrm{J}^\mu_{\mathrm{EM}}|{}^8\mathrm{Be}^*\rangle &= \frac{e}{2}\langle {}^8\mathrm{Be}|\mathrm{J}^\mu_0|{}^8\mathrm{Be}^*\rangle + \frac{\mathrm{e}}{2}\langle {}^8\mathrm{Be}|\mathrm{J}^\mu_1|{}^8\mathrm{Be}^*\rangle \\ \langle {}^8\mathrm{Be}|\mathrm{J}^\mu_{\mathrm{X}}|{}^8\mathrm{Be}^*\rangle &= \frac{e}{2}(\epsilon_p+\epsilon_n)\langle {}^8\mathrm{Be}|\mathrm{J}^\mu_0|{}^8\mathrm{Be}^*\rangle + \frac{\mathrm{e}}{2}(\epsilon_\mathrm{p}-\epsilon_\mathrm{n})\langle {}^8\mathrm{Be}|\mathrm{J}^\mu_1|{}^8\mathrm{Be}^*\rangle\end{aligned}$$

In the limit that ${}^8\mathrm{Be}^*$ is pure isosinglet

$$\langle {}^8\mathrm{Be}|\mathrm{J}^\mu_1|{}^8\mathrm{Be}^*\rangle = 0$$

Hence

$$\Lambda_X = \Lambda_\gamma$$

Rates

Then

$$\frac{\Gamma\left({}^8\mathrm{Be}^* \to \ {}^8\mathrm{Be}+\mathrm{X}\right)}{\Gamma\left({}^8\mathrm{Be}^* \to \ {}^8\mathrm{Be}+\gamma\right)} = (\epsilon_p + \epsilon_n)^2 \ \frac{|\vec{k}_X|^3}{|\vec{k}_\gamma|^3} = 5.8 \times 10^{-6}$$

with $|\vec{k}_X| = 6.35\ \mathrm{MeV},\ \ |\tilde{\mathrm{k}}_\gamma| = 18.15\ \mathrm{MeV}$

$$\epsilon_p + \epsilon_n = 0.01$$

or

$$\epsilon_u + \epsilon_d = 3.3 \times 10^{-3}$$

Rates - Isospin Mixing & Violation

- States are isospin admixtures

$$\begin{cases} |^8\mathrm{Be}^* \rangle = \beta|0\rangle - \alpha|1\rangle \\ |^8\mathrm{Be}^{*\prime}\rangle = \alpha|0\rangle + \beta|1\rangle \end{cases} \qquad \alpha^2 + \beta^2 = 1$$

- take into account isospin breaking, $\Delta T = 1$ suprion
-

$$\begin{aligned} \langle ^8\mathrm{Be}|\mathrm{J}^\mu_{\mathrm{EM}}|^8\mathrm{Be}^*\rangle &\propto \beta M1_{T=0} - \alpha M1_{T=1} + \kappa\beta M1_{T=1} \\ \langle ^8\mathrm{Be}|\mathrm{J}^\mu_{\mathrm{X}}|^8\mathrm{Be}^*\rangle &\propto (\epsilon_p + \epsilon_n)\beta M1_{T=0} + (\epsilon_p - \epsilon_n)\left(-\alpha M1_{T=1} + \kappa\beta M1_{T=1}\right) \end{aligned}$$

with

$$M1_{T=0} = 0.014(1)\mu_N \qquad M1_{T=0} = 0.767(9)\mu_N$$

Pastore et al., Phys.Rev. C90 (2014) no.2, 024321

Rates - Isospin Mixing & Violation

One finds

$$\frac{\Gamma_X}{\Gamma_\gamma} = \left| \frac{(\epsilon_p + \epsilon_n)\beta M1_{T=0} + (\epsilon_p - \epsilon_n)\left(-\alpha M1_{T=1} + \kappa\beta M1_{T=1}\right)}{\beta M1_{T=0} - \alpha M1_{T=1} + \kappa\beta M1_{T=1}} \right|^2 \frac{|\vec{k}_X|^3}{|\vec{k}_\gamma|^3}$$

Anomalous Nucleon Magnetic Momemnts

Our theory is microscopic

$$J_X^\mu X_\mu = e\left(\epsilon_u \bar{u}\gamma^\mu u + \epsilon_d \bar{d}\gamma^\mu d + \ldots\right) X_\mu$$

Can be mapped to Nucleon level $N = \begin{pmatrix} p \\ n \end{pmatrix}$ " =" $\begin{pmatrix} 2u + d' \\ 2d + u \end{pmatrix}$

$$\epsilon_p = 2\epsilon_u + \epsilon_d \qquad \epsilon_n = 2\epsilon_d + \epsilon_u$$

J_X - vector current. Decomposed to vector current

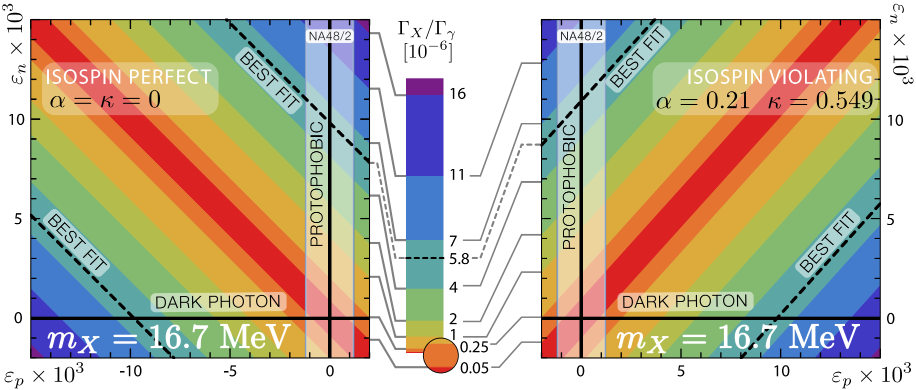
$$\begin{cases} J_0^\mu = \bar{N}\gamma^\mu N = J_p^\mu + J_n^\mu = J_u^\mu + J_d^\mu & \text{isosinglet} \\ J_1^\mu = \bar{N}\gamma^\mu T^3 N = J_p^\mu - J_n^\mu = J_u^\mu - J_d^\mu & \text{isovector} \end{cases}$$

For the rate we calculate

$$\langle {}^8\mathrm{Be}|\mathrm{J}_\mathrm{X}^\mu|{}^8\mathrm{Be}^*\rangle \Leftrightarrow \langle {}^8\mathrm{Be}|\mathrm{M1}|{}^8\mathrm{Be}^*\rangle$$

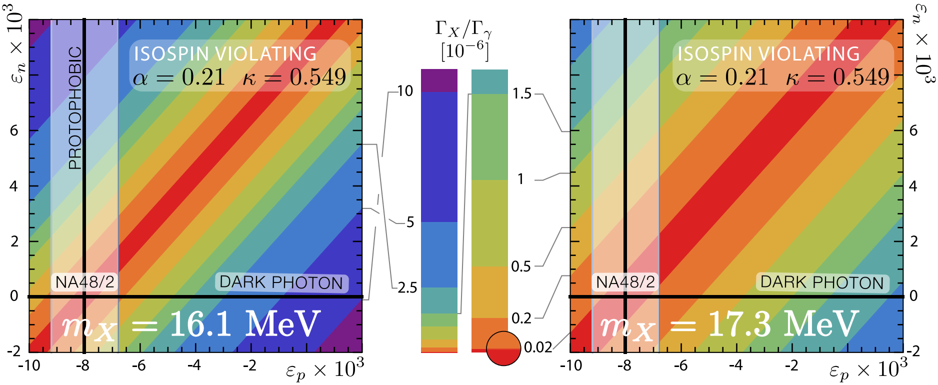
where $M1$ include all Nuclear & Nucleon level effects, including magnetic moments - which are QCD dominated !

Plots



ISOSPIN PERFECT
$\alpha = \kappa = 0$
BEST FIT
BEST FIT
PROTOPHOBIC
NA48/2
DARK PHOTON
$m_X = 16.7$ MeV
$\varepsilon_n \times 10^3$
$\varepsilon_p \times 10^3$
-10
-5
0
5
10
Γ_X/Γ_γ $[10^{-6}]$
16
11
7
5.8
4
2
1
0.25
0.05
ISOSPIN VIOLATING
$\alpha = 0.21$ $\kappa = 0.549$
BEST FIT
BEST FIT
PROTOPHOBIC
NA48/2
DARK PHOTON
$m_X = 16.7$ MeV
$\varepsilon_n \times 10^3$
$\varepsilon_p \times 10^3$
0
5
10

Plots



ISOSPIN VIOLATING
$\alpha = 0.21 \quad \kappa = 0.549$
PROTOPHOBIC
NA48/2
DARK PHOTON
$m_X = 16.1$ MeV
$\varepsilon_n \times 10^3$
$\varepsilon_p \times 10^3$
Γ_X/Γ_γ
$[10^{-6}]$
10
5
2.5
1.5
1
0.5
0.2
0.02
ISOSPIN VIOLATING
$\alpha = 0.21 \quad \kappa = 0.549$
NA48/2
DARK PHOTON
$m_X = 17.3$ MeV

Pseudo-Scalar (ALP)

Same approach

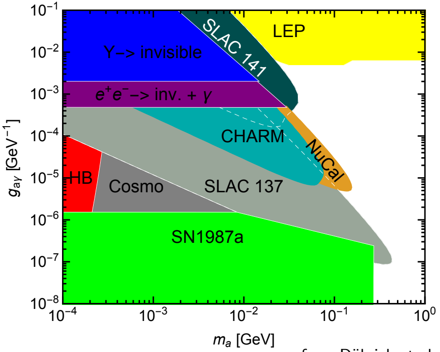
$$J^\pi(^8\text{Be}) = 0^+ \quad \Longleftarrow \quad J^\pi(^8\text{Be}^*) = 1^+ \quad \Longrightarrow \quad J^\pi(X) = 0^-$$

Parity conserving: $P_{\text{initial}} = (+) = (+) = (+)(-)(-)^{L=1} = P_{\text{final}}$

ALP searches exclude:

$10^{-18}\ \text{GeV}^{-1} < g_{X\gamma\gamma} < 10^{-1}\ \text{GeV}^{-1}$

Döbrich et al. arXiv:1512.03069
Hewett et al., arXiv:1205.2671



from Döbrich et al.

Recently Ellwanger & Morreti, arXiv:1609.01669

$g_{Xee} \Rightarrow$ Decay in Dump

no constraint

Other Vector Avenues

- pure $B - L$:
  $g_{B-L}\big|_{m\sim 17\ \mathrm{MeV}} < 2 \times 10^{-5} \quad \Longrightarrow \quad$ cannot account for signal

- Axial vectors - avoid π^0 decay bounds (Sutherland-Veltman) worry about
  - Matching to nuclear theory
  - Atomic Parity Violation constraints
  - enhanced contributions to constrained observables
    cf $\phi \to \eta X$ and $(g-2)_\ell$

The $U(1)_{B-L}$ Model

$$\epsilon_\psi = \epsilon_{B-L} Q_\psi^{B-L} + \epsilon Q_\psi^{EM} \quad \Longrightarrow \quad \begin{cases} \epsilon_p = \epsilon_{B-L} + \epsilon \\ \epsilon_n = \epsilon_{B-L} \\ \epsilon_e = -\epsilon_p \\ \epsilon_\nu = -\epsilon_n \end{cases}$$

- Q-(B-L) in protophobic limit
- Anomaly free with ν_Rs.
- For $(\epsilon_p, \ |\epsilon_n|) \approx (< 0.001, \ 0.002 - 0.008)$ fits $^8\mathrm{Be}$ and π^0 constraint. Nontrivial ϵ_e in the correct range. & $\epsilon_\mu \approx \epsilon_e$ (and also account for $(g-2)_\mu$.
- ϵ_ν too large $\Rightarrow$ ν-neutralization.
- $\langle h_X \rangle \approx 14 \ \mathrm{GeV} \frac{0.002}{|\epsilon_{\mathrm{B-L}}|}$ breaks $U(1)_{B-L}$ and generates: $m_X, \ m_\nu^{Majorana}, \nu - \nu_D$-mixing

Related Work

1. Can nuclear physics explain the anomaly observed in the internal pair production in the Beryllium-8 nucleus? Xilin Zhang, Gerald A. Miller. arXiv:1703.04588 [nucl-th]
2. Light Axial Vectors, Nuclear Transitions, and the 88Be Anomaly By J. Kozaczuk, D. E. Morrissey, S.R. Stroberg. arXiv:1612.01525 [hep-ph]
3. Light Weakly Coupled Axial Forces: Models, Constraints, and Projections By Yonatan Kahn, Gordan Krnjaic, Siddharth Mishra-Sharma, Tim M. P. Tait. arXiv:1609.09072 [hep-ph].
4. The 17 MeV Anomaly in Beryllium Decays and $U(1)$ Portal to Dark Matter By Chian-Shu Chen, Guey-Lin Lin, Yen-Hsun Lin, Fanrong Xu. arXiv:1609.07198 [hep-ph].
5. Possible Explanation of the Electron Positron Anomaly at 17 MeV in ^{8}Be Transitions Through a Light Pseudoscalar By Ulrich Ellwanger, Stefano Moretti. arXiv:1609.01669 [hep-ph].
6. The Protophobic Light Vector Boson as a Mediator to the Dark Sector By Teppei Kitahara, Yasuhiro Yamamoto. arXiv:1609.01605 [hep-ph].
7. The 17 MeV Anomaly in Beryllium Decays and $U(1)$ Portal to Dark Matter By Chian-Shu Chen, Guey-Lin Lin, Yen-Hsun Lin, Fanrong Xu. arXiv:1609.07198 [hep-ph].
8. The new interaction suggested by the anomalous ^{8}Be transition sets a rigorous constraint on the mass range of dark matter By Lian-Bao Jia, Xue-Qian Li. arXiv:1608.05443 [hep-ph].
9. X(16.7) as the Solution of NuTeV Anomaly By Yi Liang, Long-Bin Chen, Cong-Feng Qiao. arXiv:1607.08309 [hep-ph].
10. Neutrinophilic nonstandard interactions By Yasaman Farzan, Julian Heeck. arXiv:1607.07616 [hep-ph]. 10.1103/PhysRevD.94.053010. Phys.Rev. D94 (2016) no.5, 053010.
11. X(16.7) Production in Electron-Positron Collision By Long-Bin Chen, Yi Liang, Cong-Feng Qiao. arXiv:1607.03970 [hep-ph].
12. Realistic model for a fifth force explaining anomaly in $^{8}Be^{*} \to {}^{8}Be\ e^{+}e^{-}$ Decay By Pei-Hong Gu, Xiao-Gang He. arXiv:1606.05171 [hep-ph].

New Boson ?

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.

DOI: 10.1103/PhysRevLett.116.042501