Light Axial Vectors, Nuclear Transitions, and the ^{8}Be Anomaly

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U.S. Cosmic Visions: New Ideas in Dark Matter

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Some References

Primarily based on **JK, D. Morrissey, and S.R. Stroberg**, arXiv:1612.01525 [hep-ph]

See also:

Krasznahorkay et al, *PRL* 116 (2016) no.4, 042501

Feng et al, *PRL* 117 (2016) no.7, 071803
PRD 95 (2017) no.3, 035017

Kahn et al, arXiv:1609.09072 [hep-ph]

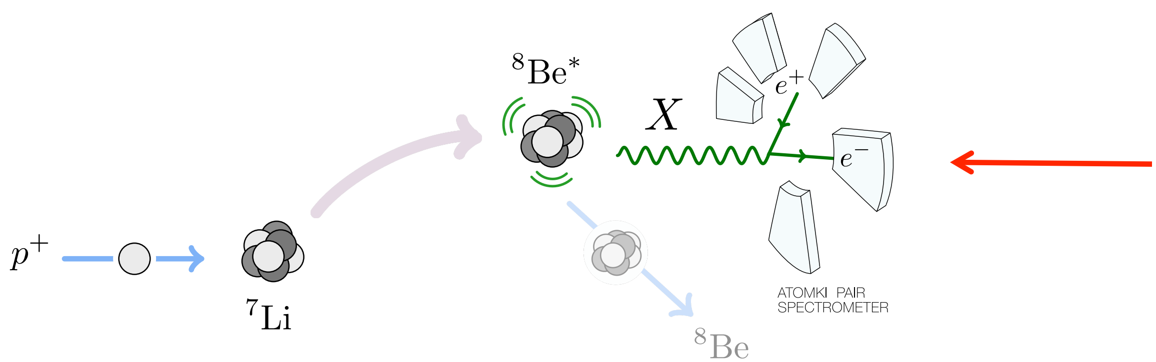
This workshop:

Iftah Galon's slides

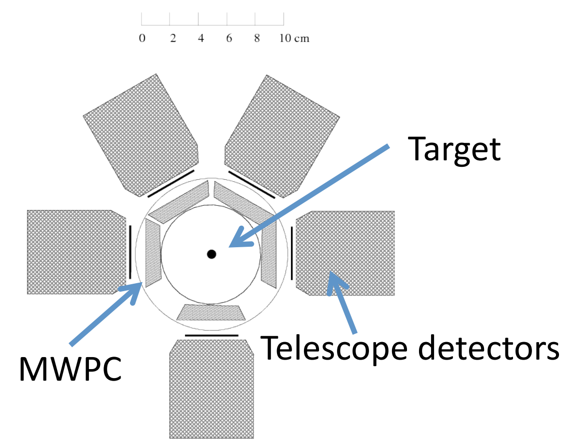
Subsequent talks by Xilin Zhang, Rafael Lang, and Kyle Leach

The Atomki Experiment in a Nutshell

Search for internal pair creation ($e^+ e^-$ production) in excited states of ^{8}Be



Feng et al, 2016



Gulyas et al, 2015

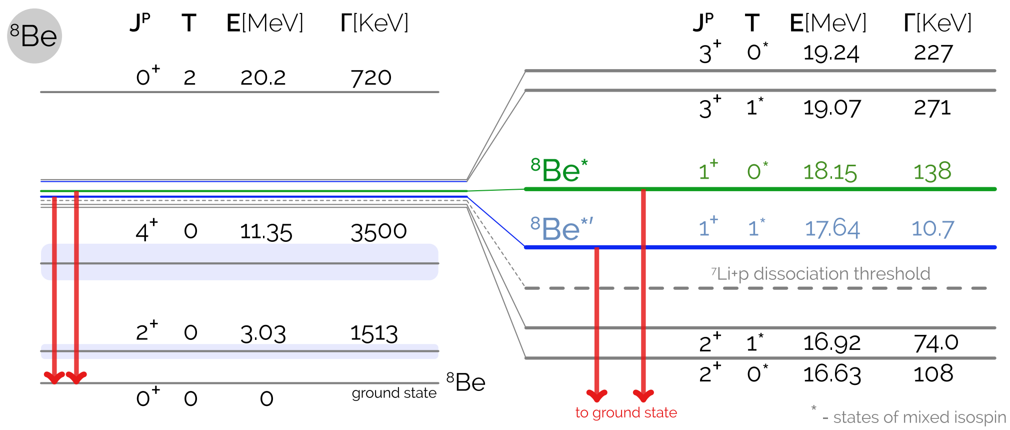
1.0 μA proton beam from Van de Graaf generator impinge on LiF_2, LiO_2 targets

$e^+ e^-$ energies and angles determined by 5 plastic telescope detectors (scintillator + PMT) and multi-wire proportional chambers

The Atomki Experiment in a Nutshell

Proton beam energy tuned to excite *J=1* ^{8}Be states

Feng et al, 2016



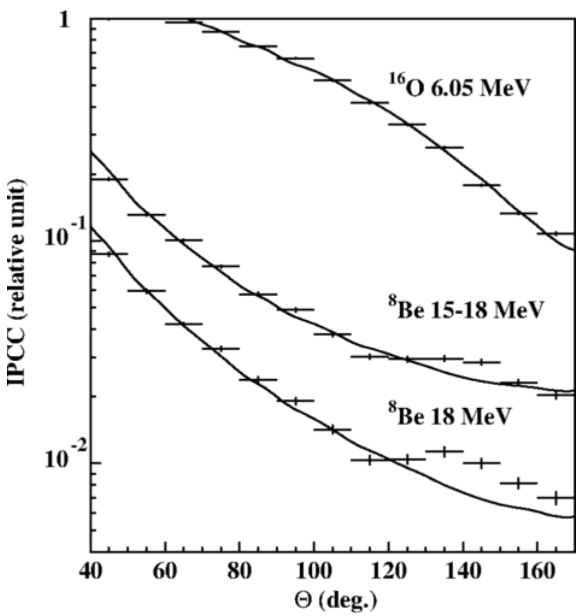
Detector calibrated using internal pair creation in ^{12}C and ^{16}O

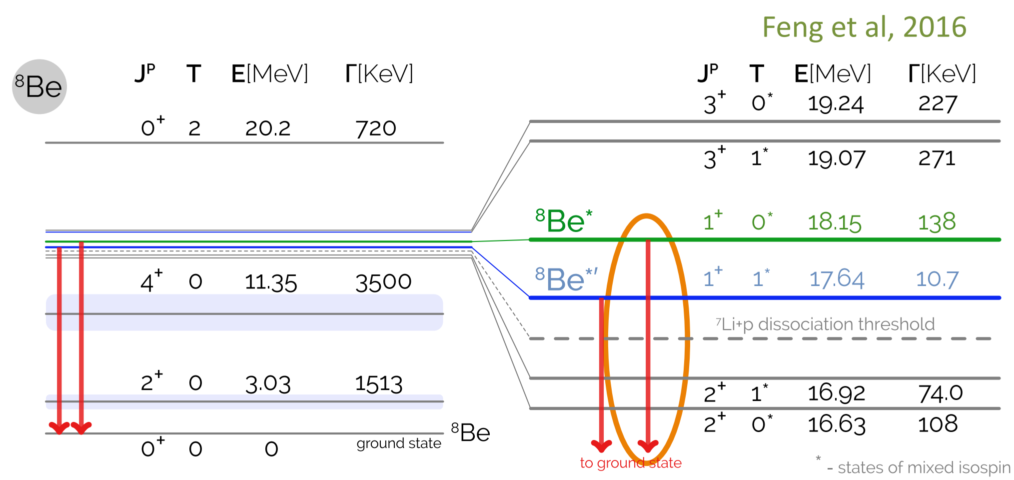
One week-long experiments at each bombarding energy, targets periodically changed

The Atomki Results

Krasznahorkay et al, 2016

Isoscalar transition features significant bump-like excess in $e^+ e^-$ opening angle and invariant mass spectrum (**6.8 σ**)





No corresponding excess in the isovector ($^8Be^{*\prime}$) transition

The Atomki Interpretation

Krasznahorkay et al, 2016

Interpretation put forward by collaboration: **light gauge boson**

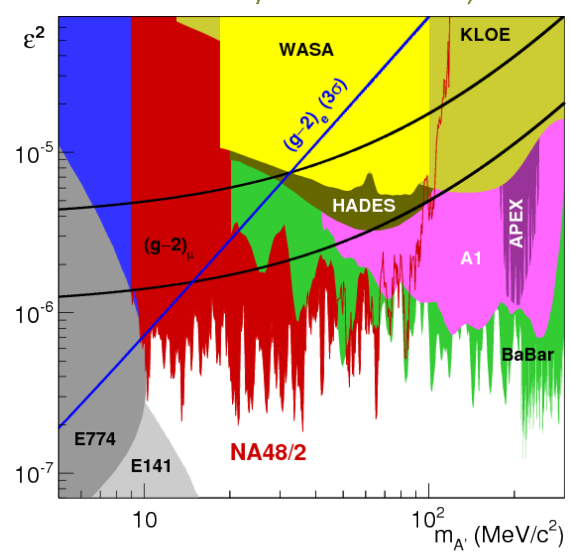
$$m = 16.7 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})\,\text{MeV}$$

$$\frac{\Gamma(^8\text{Be}' \to ^8 \text{Be}X)}{\Gamma(^8\text{Be}' \to ^8 \text{Be}\gamma)}\text{Br}(X \to e^+e^-) = 5.8 \times 10^{-6}$$

In the Atomki *PRL* the collaboration claimed this to be consistent with a standard dark photon featuring $\varepsilon^2 \sim 10^{-7}$

Feng et al (2016) pointed out that explaining the Atomki result actually requires $\epsilon \approx 0.011$, which is excluded, in particular by NA48/2

NA48/2 Collaboration, 2015



A Protophobic Vector Explanation

Feng et al, 2016 (PRL + PRD)

Assume more general vector setup

$$\mathcal{L} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu - X^\mu J_\mu \,, \;\; J_\mu = \sum_f e\varepsilon_f \bar{f}\gamma_\mu f$$

The NA48/2 constraint arises from $\pi^0 \to X\gamma$ decays. Rate proportional to axial anomaly trace factor $(\varepsilon_u q_u - \varepsilon_d q_d)^2$

General setup can work provided X is protophobic,

$$|2\varepsilon_u + \varepsilon_d| \; = \; |\varepsilon_p| \; \lesssim \; \frac{(0.8-1.2)\times 10^{-3}}{\sqrt{\mathrm{Br}(X\to e^+e^-)}}$$ (NA48/2 bound)

$$|\varepsilon_n| = (2-10)\times 10^{-3}$$ (large enough rate; some caveats here)

$$\frac{|\varepsilon_e|}{\sqrt{\mathrm{Br}(X\to e^+e^-)}} \gtrsim 1.3\times 10^{-5}$$ (prompt decays)

See Iftah Galon's slides for more details

An Axial Vector Explanation

Another potential explanation: **light axial vector** JK, D. Morrissey, S. Stroberg, 2016

$$-\mathscr{L} \supset X_\mu \sum_q g_q \bar{q} \gamma^\mu \gamma^5 q$$

Axial anomaly does not contribute to $\pi^0 \to X\gamma$ in this case and so *X* does not have to be protophobic

Also, less momentum suppression (*L=0* vs *L=1* in vector case)

$$\mathcal{L}_A = \frac{g_A}{\Lambda_A} {}^8\mathrm{Be}\, G^{\mu\nu} F^{(A)}_{\mu\nu} \Longrightarrow \overline{\mathcal{M}^2}_{{}^8\mathrm{Be}^* \to {}^8\mathrm{Be}X} = \frac{4}{3}\frac{g_A^2}{\Lambda^2} M^2 m_X^2 \left(3 + 2\frac{|\vec{p}_X|^2}{m_X^2}\right)$$

↑ Leading term for vector

Challenge: have to do some nuclear physics

An Axial Vector Explanation

In the vector case, nuclear matrix elements cancel (in the pure isospin limit)

$$\frac{\Gamma(^8\mathrm{Be}^* \to ^8\mathrm{Be}X)}{\Gamma(^8\mathrm{Be}^* \to ^8\mathrm{Be}\gamma)} \propto \frac{\langle ^8\mathrm{Be}\,|J_X^\mu|^8\,\mathrm{Be}^*\rangle}{\langle ^8\mathrm{Be}\,|J_{\mathrm{EM}}^\mu|^8\,\mathrm{Be}^*\rangle} = \frac{(\varepsilon_p+\varepsilon_n)\langle ^8\mathrm{Be}\,|\bar{N}\gamma^\mu N|^8\,\mathrm{Be}^*\rangle}{\langle ^8\mathrm{Be}\,|\bar{N}\gamma^\mu N|^8\,\mathrm{Be}^*\rangle} = \varepsilon_p+\varepsilon_n$$

Cancellation does not hold in the axial vector case

$$\frac{\Gamma(^8\mathrm{Be}^* \to ^8\mathrm{Be}X)}{\Gamma(^8\mathrm{Be}^* \to ^8\mathrm{Be}\gamma)} \propto \frac{\langle ^8\mathrm{Be}\,|J_X^\mu|^8\,\mathrm{Be}^*\rangle}{\langle ^8\mathrm{Be}\,|J_{\mathrm{EM}}^\mu|^8\,\mathrm{Be}^*\rangle} = \frac{a_0\langle ^8\mathrm{Be}\,|\bar{N}\gamma^\mu\gamma^5 N|^8\,\mathrm{Be}^*\rangle}{\langle ^8\mathrm{Be}\,|\bar{N}\gamma^\mu N|^8\,\mathrm{Be}^*\rangle}$$

← Need matrix element

Here $a_0 = 2(\Delta u + \Delta d)(\epsilon_u + \epsilon_d) + 4\Delta s \epsilon_s$ relates nucleon to quark operators, with current $J_\mu^X = \sum_f \varepsilon_f \bar{f}\gamma_\mu\gamma_5 f$

An Axial Vector Explanation

How large do the couplings have to be?

$$-\mathscr{L} \supset X_\mu \sum_q g_q \bar{q} \gamma^\mu \gamma^5 q \longrightarrow \langle N | \sum_q g_q \bar{q} \gamma^\mu \gamma^5 q | N \rangle = \delta_i^\mu \sigma^i \sum_q g_q \Delta q^{(N)}$$

Quark-level interaction

Nucleon-level operators

Decay width for J = 1 → 0 transitions (at leading order in k/m_N expansion):

$$\longrightarrow \Gamma = \frac{k}{18\pi} \left(2 + \frac{E_k^2}{m_X^2} \right) \left| a_n \langle 0 || \sigma^n || 1 \rangle + a_p \langle 0 || \sigma^p || 1 \rangle \right|^2$$

Reduced matrix elements of spin operators acting on all nucleons of a given type in the nucleus

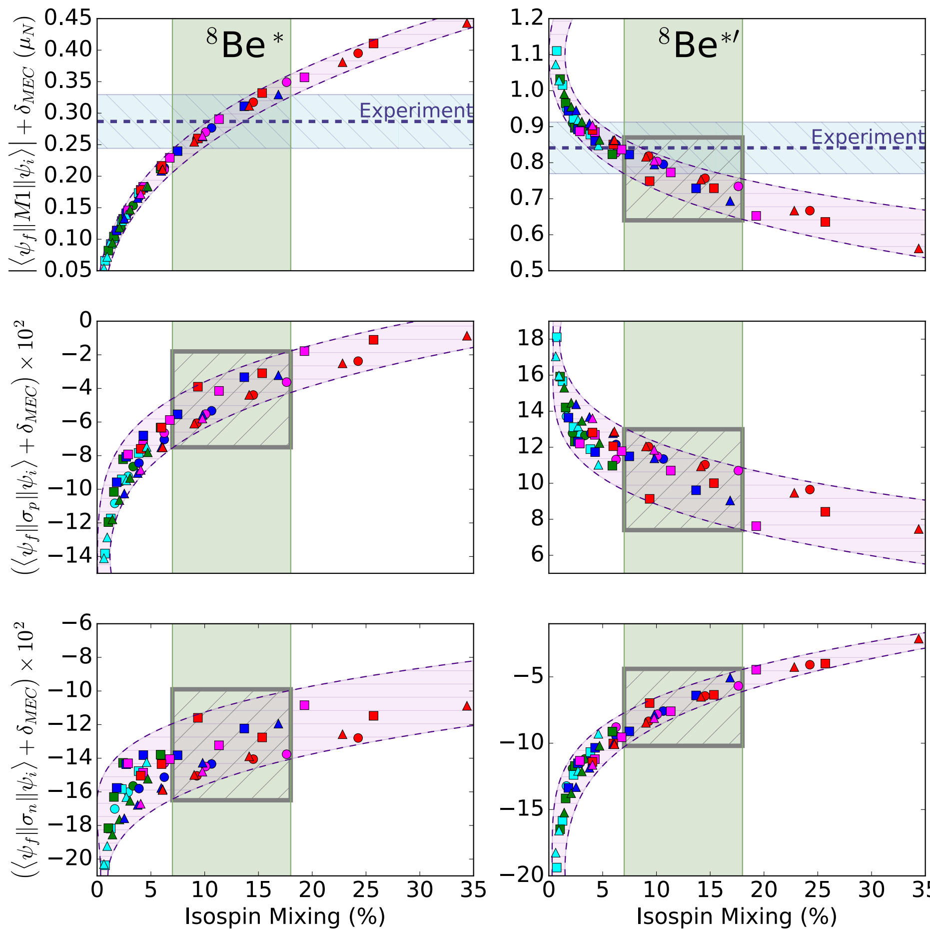
Need to compute $\langle 0 || \sigma^{p,n} || 1 \rangle$ for the ^{8}Be states of interest

Matrix Elements

Full *ab-initio* calculation of the matrix elements

Utilizes the In-Medium Similarity Renormalization Group (IM-SRG) with forces derived from chiral effective theory (NN + 3N) and including effects from meson exchange currents (MECs)

Fix isospin mixing fraction from *M1* isoscalar transition to extract predictions for the other matrix elements



Matrix Elements

Results:

Matrix element	Prediction
$\langle 0^+ \Vert M1 \Vert \mathcal{V} \rangle$ (μ_N)	0.76(12)
$\langle 0^+ \Vert \sigma_p \Vert \mathcal{V} \rangle$	0.102(28)
$\langle 0^+ \Vert \sigma_n \Vert \mathcal{V} \rangle$	−0.073(29)
$\langle 0^+ \Vert \sigma_p \Vert \mathcal{S} \rangle$	−0.047(29)
$\langle 0^+ \Vert \sigma_n \Vert \mathcal{S} \rangle$	−0.132(33)

Things to note:

-Relative sign between the proton and neutron matrix elements for the $^8Be^{*\prime}$ transition, but not for $^8Be^*$, results in suppression of isovector rate

-Significant error bars (can be improved in the future) but results enough to begin scrutiny of the axial vector scenario

Implications for the ^{8}Be Anomaly

Obtain range of couplings required to explain the Atomki result

Requirements depend on precise mass (need more info from experimentalists)

From Feng et al, 2016:

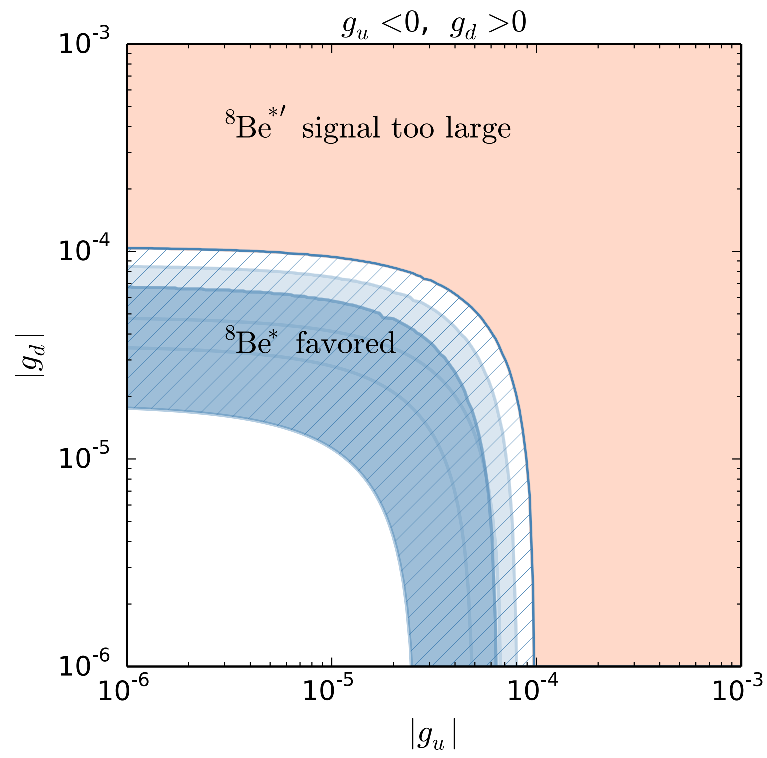
$$m_X \simeq 16.7\,\mathrm{MeV}, \qquad \frac{\Gamma_{^8\mathrm{Be}^* \to {^8\mathrm{Be}}\,X}}{\Gamma_{^8\mathrm{Be}^* \to {^8\mathrm{Be}}\,\gamma}} \simeq 5.8 \times 10^{-6}$$

$$m_X \simeq 17.3\,\mathrm{MeV}, \qquad \frac{\Gamma_{^8\mathrm{Be}^* \to {^8\mathrm{Be}}\,X}}{\Gamma_{^8\mathrm{Be}^* \to {^8\mathrm{Be}}\,\gamma}} \simeq 2.3 \times 10^{-6}$$

$$m_X \simeq 17.6\,\mathrm{MeV}, \qquad \frac{\Gamma_{^8\mathrm{Be}^* \to {^8\mathrm{Be}}\,X}}{\Gamma_{^8\mathrm{Be}^* \to {^8\mathrm{Be}}\,\gamma}} \simeq 5.0 \times 10^{-7}$$

Demand that the corresponding isovector transition rate is not too large to conflict with null results (Feng et al, 2016)

$$\frac{\Gamma_{^8\mathrm{Be}^* \to {^8\mathrm{Be}}\,X}}{\Gamma_{^8\mathrm{Be}^* \to {^8\mathrm{Be}}\,\gamma}} > 5 \times \frac{\Gamma_{^8\mathrm{Be}^{*\prime} \to {^8\mathrm{Be}}\,X}}{\Gamma_{^8\mathrm{Be}^{*\prime} \to {^8\mathrm{Be}}\,\gamma}}$$



Other Constraints

What about other constraints? And UV completion?

Impact of other constraints depend on UV completion. Our assumptions:

-Purely axial generation-independent quark couplings

-Both axial- and vector-like couplings to leptons: $\mathcal{L} \supset X_\mu \sum_i \bar{\ell}_i \left(g_i^V \gamma^\mu + g_i^A \gamma^\mu \gamma^5 \right) \ell_i$

-Vanishing couplings to neutrinos

-100% branching fraction into electron-positron pairs

These assumptions can be relaxed if so desired

Other Constraints

See also **Kahn et al, 2016** for detailed discussion of constraints on light axial vectors

Dominant constraints on lepton couplings:

Decays inside Atomki detector: $\frac{\sqrt{(g_e^V)^2 + (g_e^A)^2}}{e} \gtrsim 1.3 \times 10^{-5}$

Muon (g-2): $\left|-(g_\mu^A)^2 + 9 \times 10^{-3}(g_\mu^V)^2\right| \lesssim 1.6 \times 10^{-9}$

Electron beam dumps (SLAC E141): $\frac{\sqrt{(g_e^A)^2 + (g_e^V)^2}}{e} \gtrsim 2 \times 10^{-4}$

Electron-positron colliders (KLOE2): $\frac{\sqrt{(g_e^A)^2 + (g_e^V)^2}}{e} \lesssim 2 \times 10^{-3}$

Parity-violating Møller scattering (SLAC E158): $|g_e^V g_e^A| \lesssim 1 \times 10^{-8}$

Dominant constraints on quark couplings:

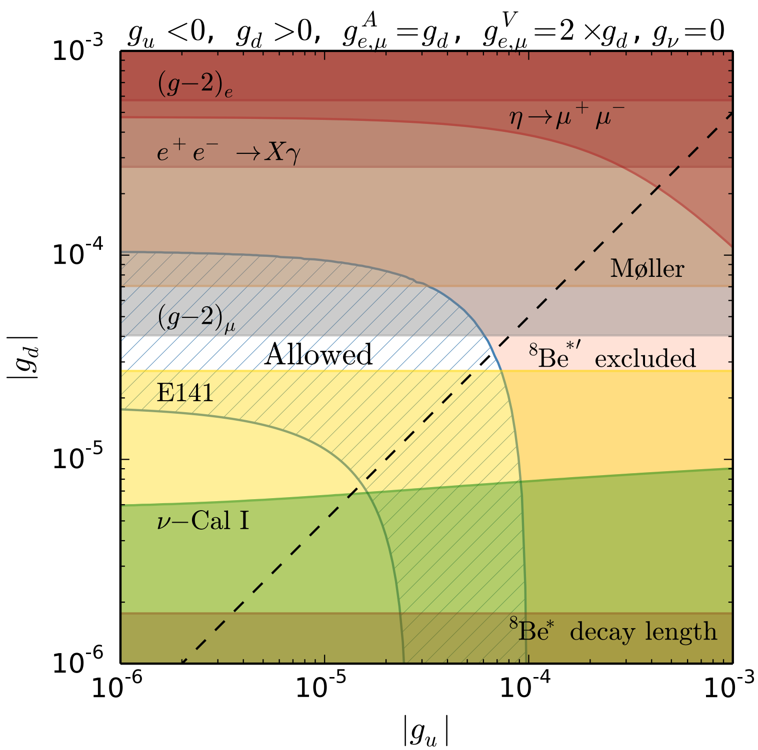
$\eta \rightarrow \mu^+ \mu^-$: $\frac{g_\mu^A (g_u + g_d - 1.5 g_s)}{(m_X/\mathrm{MeV})^2} \lesssim 4 \times 10^{-10}$

Proton fixed target experiments (ν−Cal I) (also depends on coupling to electrons)

Putting it all together

A light axial vector can be a viable explanation of the ^{8}Be anomaly

Detailed results depend on relationship between leptonic and quark couplings



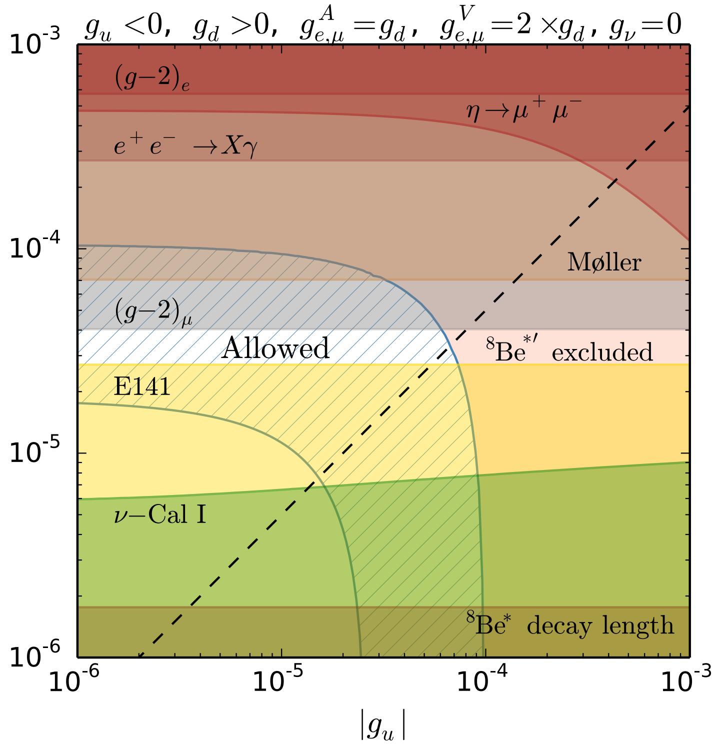
Dominant constraints on this scenario depend on leptonic couplings and are highly UV-dependent

The Atomki null result for $^8\mathrm{Be}^{*\prime}$ places the strongest model-independent constraint on the quark couplings

Relaxing our initial assumptions could potentially open up more parameter space

A UV Completion

Relationship of couplings shown can arise in a UV completion involving a dark $U(1)_{RH}$ and two Higgs doublets (see Kahn et al, 2016)



Purely axial quark couplings + vanishing neutrino couplings (there's tuning here) results in:

$$g_u = -2g_d, \qquad g^A_{e,\mu} = g_d, \qquad g^V_{e,\mu} = 2g_d$$

Also require vector-like fermions (+ dark Higgses) to cancel anomalies. LHC limits on "anomalons" yield upper bound on couplings (subdominant to ^{8}Be$^{*\prime}$ limit) [Kahn et al, 2016]

Results stress importance of complementarity and of probing both quark and leptonic couplings

Future Experiments

Many planned experiments should have an impact on the light (axial) vector scenario

See e.g. Feng et al, 2016; Kahn et al, 2016

Lepton Couplings:

VEPP-3, DarkLight, MESA, Belle II, HPS, APEX, PADME…

Quark couplings:

LHCb, ShiP, SeaQuest …

Other nuclear decay experiments (including independent verification of the Atomki result!)

Takeaways

-A light vector axially coupled to quarks can explain the ^{8}Be anomaly and exist in a viable UV-complete theory

-If the anomaly goes away, we have a new constraint on light axially-coupled vectors (already have a new constraint from ^{8}Be*')

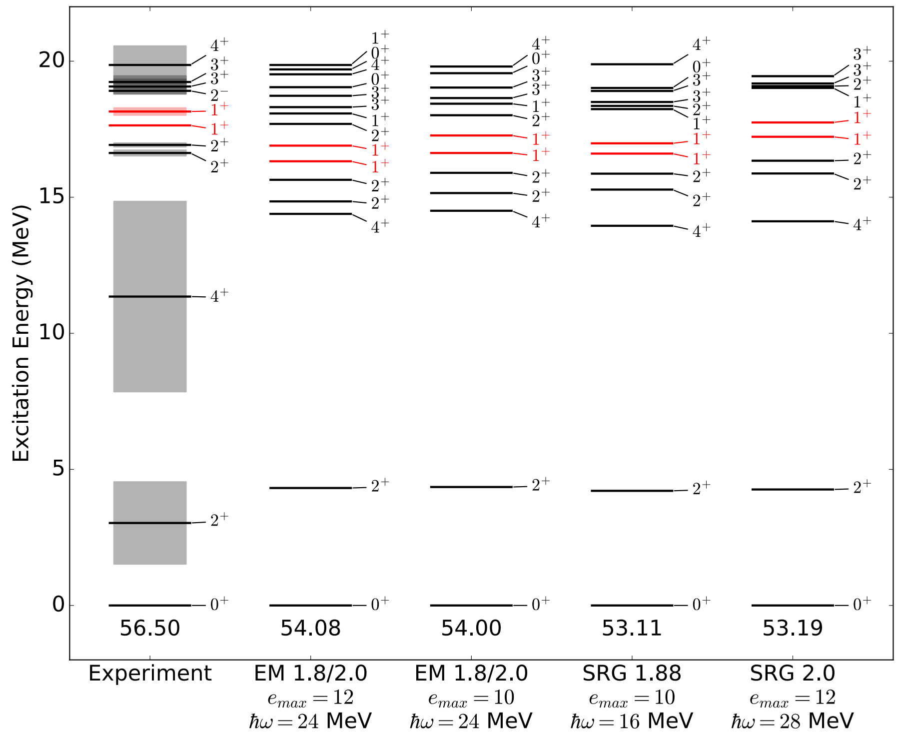
-Important to target both lepton and quark couplings

-Are there other nuclear systems that can be useful in discovering or constraining light new vectors that are otherwise difficult to probe?

Backup

Ab Initio Predictions for ^{8}Be

IM-SRG calculations reproduce the observed ^{8}Be spectrum



A UV Completion

Repurpose model from **Kahn et al, 2016**

RH SM fermions charged under new $U(1)_{RH}$ with gauge coupling g_D

Kinetic mixing ε with hypercharge

Require two Higgs doublets for SM fermion mass terms: $\mathcal{L}_{\mathcal{Y},2\mathrm{HDM}} = y_u H_u Q u^c + y_d H_d Q d^c + y_e H_d L e^c + \mathrm{h.c.}$

Require vector-like fermions (+ two dark Higgs doublets) to cancel anomalies

$\mathcal{L} = \mathcal{L}_{\mathcal{Y},2\mathrm{HDM}} + y_{\mathcal{U}} H'_u \mathcal{U}\mathcal{U}^c + y_{\mathcal{D}} H'_d \mathcal{D}\mathcal{D}^c + y_{\mathcal{E}} H'_d \mathcal{E}\mathcal{E}^c + \mathrm{h.c.}$

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{RH}$
H_u	$\mathbf{1}$	$\mathbf{2}$	$+\frac{1}{2}$	$+q_{H_u}$
H_d	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$+q_{H_d}$
u^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$-q_{H_u}$
d^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$+\frac{1}{3}$	$-q_{H_d}$
e^c	$\mathbf{1}$	$\mathbf{1}$	$+1$	$-q_{H_d}$
$\mathcal{U}$	$\mathbf{3}$	$\mathbf{1}$	$+\frac{2}{3}$	$+q_{H_u}$
$\mathcal{U}^c$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	0
$\mathcal{D}$	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	$+q_{H_d}$
$\mathcal{D}^c$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$+\frac{1}{3}$	0
$\mathcal{E}$	$\mathbf{1}$	$\mathbf{1}$	-1	$+q_{H_d}$
$\mathcal{E}^c$	$\mathbf{1}$	$\mathbf{1}$	$+1$	0
H'_u	$\mathbf{1}$	$\mathbf{1}$	0	$-q_{H_u}$
H'_d	$\mathbf{1}$	$\mathbf{1}$	0	$-q_{H_d}$

Resulting couplings:

SM lepton	e	μ, τ
g_ℓ^V	$\frac{1}{2} g_D q_{H_d} - \epsilon e$	$\frac{1}{2} g_D q_{H_d} - \epsilon e$
g_ℓ^A	$-\frac{1}{2} g_D q_{H_d}$	$-\frac{1}{2} g_D q_{H_d}$

SM quark	u, c, t	d, s, b
g_q^V	$\frac{1}{2} g_D q_{H_u} + \frac{2}{3}\epsilon e$	$\frac{1}{2} g_D q_{H_d} - \frac{1}{3}\epsilon e$
g_q^A	$-\frac{1}{2} g_D q_{H_u}$	$-\frac{1}{2} g_D q_{H_d}$

(neutrino coupings set to 0)