Non-SUSY Origins of EDMs

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A review, supplemented with SG and Daheng He, arXiv:1302.1862, 1202.5239, and in preparation.

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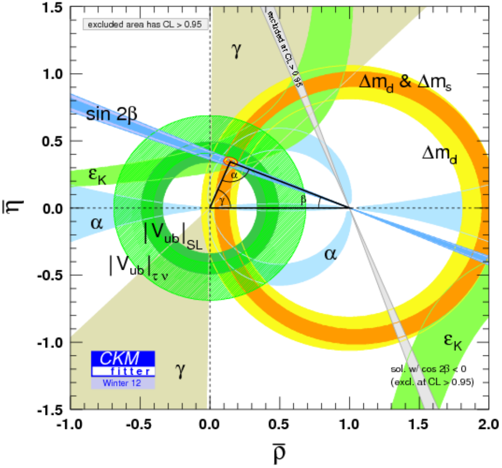


Flavor and CP violation in flavor-changing processes is dominated by the CKM mechanism.

[CKMfitter: hep-ph/0104062, hep-ph/0406184 ; http://ckmfitter.in2p3.fr – Winter, 2012 update]

But the CKM mechanism cannot explain the Baryon asymmetry of the Universe....

Evidence for New CP Phases:

We live in a known Universe of matter.

Confronting the observed ^{2}H abundance with big-bang nucleosynthesis yields a **baryon asymmetry**

$$\eta = n_{\rm baryon}/n_{\rm photon} = (5.96 \pm 0.28) \times 10^{-10}$$ [Steigman, 2012]

The particle physics of the early universe can explain this asymmetry if B, C, and CP violation exists in a non-equilibrium environment. [Sakharov, 1967]

But estimates of the baryon excess in the Standard Model are much too small, $\eta < 10^{-26}$!! [Farrar and Shaposhnikov, 1993; Gavela et al., 1994; Huet and Sather, 1995.]

Why? CP violation in the SM is special: it appears only if [Jarlskog, 1985]

$$\begin{aligned} J_{CP} &= (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_u^2)(m_s^2 - m_d^2) \\ &\times \mathrm{Im}(V_{tb} V_{td}^* V_{cd} V_{cb}^*) \neq 0 \end{aligned}$$

Now $\mathrm{Im}(V_{tb} V_{td}^* V_{cd} V_{cb}^*) \sim 3 \times 10^{-5}$ so that [Nir, SSI 2012]

$$n_{\rm baryon}/n_{\rm photon} \sim J_{CP}/T_c^{12} \sim 1 \times 10^{-19} \text{ (!)}$$

Ergo to explain the BAU there must be sources of CP violation beyond the CKM matrix.

Unanswered Questions...

There is much theoretical "evidence" that the Standard Model is incomplete — *it leaves many questions unanswered.* Here are a few.

- Why are there 3 generations? Why do the fermions have the masses and mixings they do?
- Why is the weak mass scale $\mathcal{O}(100\,\text{GeV})$?

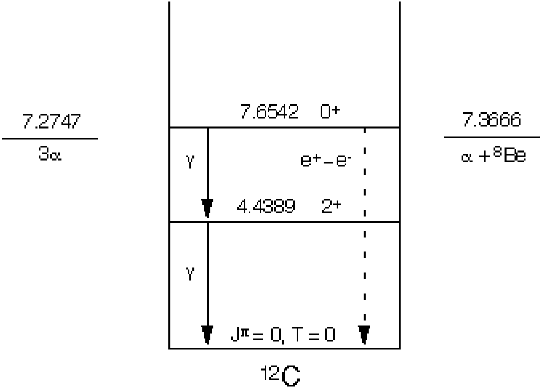
  [The Planck scale is $M_P = (G_N)^{-1/2} \approx 10^{19}$ GeV – why this "hierarchy"?]
- Why is the baryon asymmetry of the Universe its observed value?

"Why" questions need have no resolution.... However, we also *know* that the Standard Model only explains 5% of the known Universe.

There is much observational evidence for dark matter.
What is it?

[Clowe et al., astro-ph/0608407]

Some "Just-So"s



[Hoyle, 1953; Dunbar, Pixley, Wenzel, Whaling, 1953]

EDMs in extensions of the SM

Many models of electroweak-symmetry breaking also give rise to substantial EDMs.

Models with weak-scale supersymmetry are a particular stand-out.
$\Longrightarrow$ [M. Carena]

Some alternate possibilities....

Left-Right Symmetric Models
"Why is parity broken?"
[Pati, Salam, 1974; Mohapatra and Pati, 1975; Mohapatra, 1975; Mohapatra, Sejanovic, 1975]

Models with extended Higgs sectors
"Addressing the mysterious with the obscure" [Bigi, Sanda 2000]
[Lee, 1973, 1979; Weinberg, 1976] $\Longrightarrow$ [W. Altmannshofer]

Models with extra dimensions
"Why is gravity so weak?"
[Arkani-Hamed, Dimopoulos, Dvali, 1998 ; Randall, Sundrum, 1999; Appelquist, Cheng, Dobrescu, 2001]

EDMs in the Left-Right Symmetric Model

Parity violation is implemented spontaneously...

Model is based on SU(2)$_L\otimes$ SU(2)$_R\otimes$ U(1)

3 Higgs doublets are arranged to yield fermion masses and $v_L \ll v_R$. (There is a right-handed ν!)

The possibility of complex Higgs vevs yields the possibility of CP violation beyond the KM Ansatz $\Longrightarrow$ enter, e.g., $W_L - W_R$ mixing.

There are significant constraints from ΔM_K and ϵ_K, yielding already $M_{W_R} > 1$ TeV [Frere et al., 1992] and a predicted EDM of $d_n \sim 10^{-27}$ e-cm [Bigi-Sanda, 2000]

Recently the EDM has been revisited in an EFT framework. [Zhang, An, Ji, Mohapatra, 2007; Xu, Au, Ji, 2009]

There are the familiar dim-5 quark and chromo-quark EDM operators, as well as dim-6 4-quark operators....

The authors argue that the dim-6 operators dominate to yield from d_n and ϵ_K a lower bound on $M_{W_R} = 10 \pm 3$ TeV. (!)

We do know most dark matter must be...

- stable or effectively so on Gyr time scales
- not “hot” – i.e., not relativistic at the time it decoupled from ordinary matter in the cooling early Universe
- have no substantial strong or electromagnetic charge

As-yet-unknown symmetries in the dark sector could explain these features.

How do we discover them?

The Standard Model provides no suitable dark-matter candidate, but the Minimially Supersymmetric Standard Model (MSSM) does....

If Dark Matter is not a WIMP...

its relic density need not be fixed by thermal freezeout, and its stability need not be guaranteed by a discrete symmetry.

What mechanisms then are operative and how do we discover them?

Some possibilities...

- Its stability may be guaranteed by a hidden gauge symmetry.

  E.g., dark matter can possess a hidden U(1) symmetry. If the gauge mediator is massless, dark matter can have a **millicharge.**

  [B. Holdom, PLB 1986; Pospelov, Ritz, arXiv:0810.1502; Fox, Poppitz, arXiv:0811.0399 ...]

- Its relic density may be related to Ω_B.

  If so, dark matter ought be **asymmetric.**

  [Nussinov, PLB 1985; Barr, Chivukula, Farhi, PLB 1990; Harvey and Turner, PRD 1990; Ellis et al., NPB 1992. Ryttov and Sannino, arXiv:0809.0713 [hep-ph]; Kaplan, Luty, Zurek, arXiv:0901.4117 [hep-ph].]

A Common Origin for Baryonic and Dark Matter?

We live in a known Universe of matter.

Confronting the observed ^{2}H abundance with big-bang nucleosynthesis yields a **baryon asymmetry**

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One can connect the origin of baryonic and dark matter in different ways.
i) Dark and ordinary matter can carry a common quantum number.
ii) Net "baryon number" is zero, with $n_B = -n_D$. [Davoudiasl and Mohapatra, arXiv:1203.1247]

Asymmetric Dark Matter

Our review is **not** exhaustive; we consider just samples of classes of models.

i) **A baryon asymmetry is formed and transferred to dark matter.** [DB Kaplan, PRL 1992; ... DE Kaplan, Luty, Zurek, PRD 2009]

A B-L asymmetry generated at high T is transferred to DM which carries a B-L charge.

The relic density is set by the BAU and **not** by thermal freeze-out.

Thus $n_{\rm DM} \sim n_{\rm B}$ and $\Omega_{\rm DM} \sim (M_{\rm DM}/M_{\rm B})\Omega_{\rm B}$. Note $M_{\rm DM} \sim 5 - 15$ GeV.

ii) **A dark matter asymmetry is formed and transferred to the baryon sector.** [Shelton and Zurek, arXiv:1008.1997; Davoudiasl et al., arXiv:1008.2399; Haba and Matsumoto, arXiv:1008.2487; Buckley and Randall, arXiv:1009.0270.]

iii) **Dark matter and baryon asymmetries are formed simultaneously.** [Blennow et al, arXiv:1009.3159; Hall, March-Russell, and West, arXiv:1010.0245]

E.g., a lepton asymmetry is induced and converted to baryons and DM via new sphaleron processes from an extra non-abelian symmetry common ($SU(2)_H$) to both visible and dark sectors....

The new DM fermions are given QCD-like interactions to prevent mixing with neutrinos.

Many models contain $\gamma - \gamma'$ mixing....

Many variants exist....

Hermetic
Dark matter which is neutral under all SM gauge interactions. Suppose it possesses an exact hidden U(1). DM (here a hidden sector stau) is self-interacting and thus subject to observational constraints... e.g., $\alpha_\chi < 10^{-7}$ for $M_\chi \sim 1$ GeV.

[Feng, Kaplinghat, Tu, Yu, arXiv:0905.3039; Feng, Tu, Yu, arXiv:0808.2328]

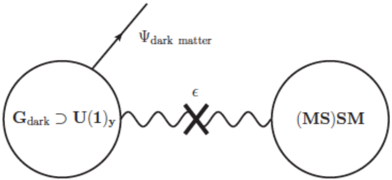
Models with Abelian Connectors
Astrophysical anomalies prompts models which mix with $U(1)_Y$.

[Essig, Schuster, Toro, 2009; Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2009; Baumgart, Cheung, Ruderman, Wang, Yavin, 2009]

Models with non-Abelian Connectors

[Baumgart, Cheung, Ruderman, Wang, Yavin, 2009; SG and He, arXiv:1302.1862]

U(1) Kinetic Mixing with a Hidden Sector



[Baumgart et al., 2009]

Let A' be the gauge field of a massive dark U(1)$'$ gauge group

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} - \frac{1}{4} F'^{,\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}$$

With $A_\mu \to \tilde{A}_\mu = A_\mu - \epsilon A'_\mu$, the A' gains a tiny electric charge ϵe.

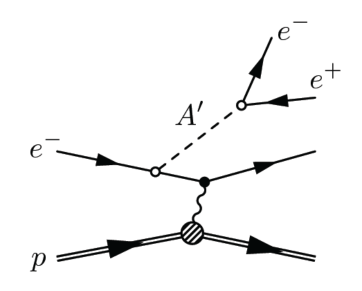
[Holdom, 1986]

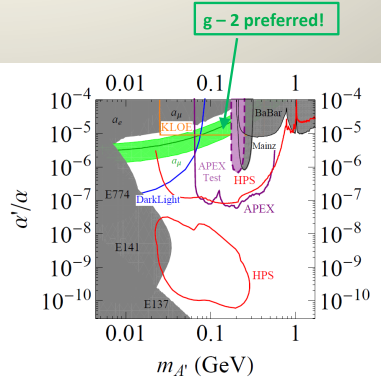
The A' can be discovered in fixed-target experiments....

[Bjorken, Essig, Schuester, Toro, arXiv:0906.0580]

New Opportunity: Search for A' at JLab

Search for new forces mediated by ~100 MeV vector boson A' with weak coupling to electrons:





Irrespective of astrophysical anomalies:

- New ~GeV–scale force carriers are important category of physics beyond the SM
- Fixed-target experiments @JLab (FEL + CEBAF) have unique capability to explore this!

Jefferson Lab   Va. Tech. Physics Colloquium Dec. 3, 2010   Thomas Jefferson National Accelerator Facility   GHP2011, R. D. McKeown   Slide 27   27

[R. McKeown, GHP 2011, April APS] [Note M. Pospelov for $g-2$ connection.]

Non-Abelian Kinetic Mixing with a Hidden Sector

Consider an operator Φ which transforms under the adjoint rep of a non-Abelian dark group. Then $\mathrm{tr}(\Phi F_{\mu\nu})\mathrm{tr}(\tilde{\Phi}\tilde{F}_{\mu\nu})$ can connect the sectors.

[Baumgart et al., 2009]

This operator should become more important at low energies.

We model this as (noting the hidden local symmetry model of QCD)

[Bando, Kugo, Uehara, Yamawaki, Yanagida, 1985]

$$\begin{aligned}
\mathcal{L}^{\pm}_{mix} &= -\frac{1}{4}\rho^{+\,\mu\nu}\rho^{-}_{\mu\nu} - \frac{1}{4}\rho'^{+\,\mu\nu}\rho'^{-}_{\mu\nu} + \frac{\epsilon}{2}\left(\rho^{+\,\mu\nu}\rho'^{-}_{\mu\nu} + \rho^{-\,\mu\nu}\rho'^{+}_{\mu\nu}\right) \\
&+ \frac{g_\rho}{\sqrt{2}}(\rho^{+}_{\mu}J^{+\,\mu} + \rho^{-}_{\mu}J^{-\,\mu})\,.
\end{aligned}$$

Under $\tilde{\rho}^{\pm}_{\mu} = \rho^{\pm}_{\mu} - \epsilon\rho'^{\pm}_{\mu}$, the baryon vector current couples to $\rho'^{\pm}$....

One can hope to detect the ρ' through its possible CP-violating effects.

A Tale of Two Models

The notion of new physics in QCD is vintage. [Okun, 1980; Bjorken, 1979; Gupta, Quinn, 1982]
Note much more recent "quirk" models:
quirks are charged under "infracolor" and are supposed to have mass $M_Q \sim 100 - 1000$ GeV, with $M_Q > \Lambda \Longrightarrow$ macroscopic strings!
The two sectors connect via

$$\mathcal{L}_{\rm eff} \sim \frac{g^2 g'^2}{16\pi^2 M_Q^4} F_{\mu\nu}^2 F_{\mu\nu}'^2$$

[Kang and Luty, arXiv:0805.4642]

For $M_Q \gtrsim 100$ GeV, weaker than the weak interactions!
Expect collider signatures only!
In our model we suppose hidden quarks crudely comparable to m_q in mass but with $\Lambda' < \Lambda$ and thus $m_{\rho'} < m_\rho$
Expect collider effects to be hidden under hadronization uncertainties!
Expect low-energy signatures only!
New physics can be an emergent low-energy feature... to be discovered at the Intensity Frontier!

Enter decay correlations...

For the neutron in a $V - A$ theory:

$$d^3\Gamma \propto E_e|\boldsymbol{p}_e|(E_e^{\max} - E_e)^2 \times \left[1 + a\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\nu}{E_e E_\nu} + \boldsymbol{P} \cdot \left(A\frac{\boldsymbol{p}_e}{E_e} + B\frac{\boldsymbol{p}_\nu}{E_\nu} + D\frac{\boldsymbol{p}_e \times \boldsymbol{p}_\nu}{E_e E_\nu}\right)\right] dE_e d\Omega_e d\Omega_\nu$$

A and B are P odd, T even, whereas D is (pseudo)T odd, P even.

In some models the severity of EDM limits make the appreciable appearance of new physics in T-odd β-decay correlations impossible.

[Herczeg (2004); note also Ng and Tulin (2012)]

Limits on permanent EDMs of nondegenerate systems and T-odd correlations in β-decays probe new sources of CP violation — all these involve spin....

In *radiative* β-decay we can form a T-odd correlation from momenta alone: $\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\nu)$, so that we probe new physics sources which are not constrained by EDM limits. [SG and Daheng He, 2012]

Anomalous interactions at low energies

What sort of interaction gives rise to a $\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\nu)$ correlation at low energy?

Harvey, Hill, and Hill: Gauging the axial anomaly of QCD under $SU(2)_L \times U(1)_Y$ makes the baryon vector current anomalous and gives rise to "Chern-Simons" contact interactions (containing $\varepsilon^{\mu\nu\rho\sigma}$) at low energy.

[Harvey, Hill, and Hill (2007, 2008)]

In a chiral Lagrangian with nucleons, pions, and a complete set of electroweak gauge fields, the requisite terms appear at N^{2}LO in the chiral expansion. [Hill (2010)]

Integrating out the $W^\pm$ yields

$$-\frac{4c_5}{M^2}\frac{eG_F V_{ud}}{\sqrt{2}}\varepsilon^{\sigma\mu\nu\rho}\bar{p}\gamma_\sigma n\bar{\psi}_{eL}\gamma_\mu\psi_{\nu_e L}F_{\nu\rho}\,,$$

which can infere with (dressed by a bremsstrahlung photon)

$$\frac{G_F V_{ud}}{\sqrt{2}}g_V\bar{p}\gamma^\mu n\bar{\psi}_e\gamma_\mu(1-\gamma_5)\psi_{\nu_e}\,,$$

Thus the weak vector current can mediate parity violation, too.

Radiative β-Decay

In $n(p_n) \to p(p_p) + e^-(l_e) + \overline{\nu}_e(l_\nu) + \gamma(k)$ decay the interference of the c_5 term with the leading $V - A$ terms yields

$$|\mathcal{M}|^2_{c_5} = 256 e^2 G_F^2 |V_{ud}|^2 \mathrm{Im}\,(c_5\, g_V) \frac{E_e}{l_e \cdot k} (\mathbf{l}_e \times \mathbf{k}) \cdot \mathbf{l}_\nu + \ldots\,,$$

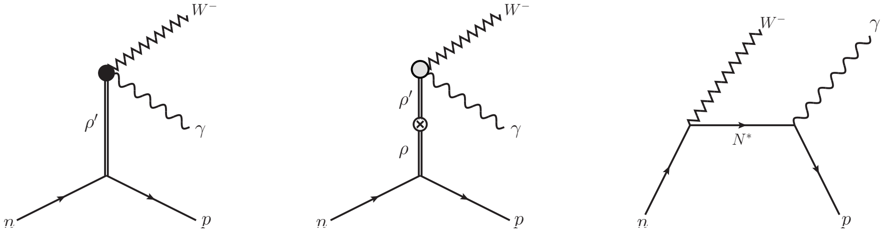
neglecting corrections of radiative and recoil order.
Note EMIT II limits $\mathrm{Im}\, g_V < 7 \cdot 10^{-4}$ (68%CL). [Mumm et al., 2011; Chupp et al., 2012]
First row CKM unitarity yields $\mathrm{Im}\, g_V < 2 \cdot 10^{-2}$ (68%CL).
Defining $\xi \equiv (\mathbf{l}_e \times \mathbf{k}) \cdot \mathbf{l}_\nu$, we form an asymmetry:

$$\mathcal{A}(\omega_{\min}) \equiv \frac{\Gamma_+(\omega_{\min}) - \Gamma_-(\omega_{\min})}{\Gamma_+(\omega_{\min}) + \Gamma_-(\omega_{\min})}\,,$$

where $\Gamma_\pm$ contains an integral of the spin-averaged $|\mathcal{M}|^2$ over the region of phase space with $\xi \gtrless 0$, respectively, neglecting corrections of recoil order.

Results

The low-energy constant c_5 can be generated in different ways....



Note that one could include a $U(1)_Y$ portal also....

This would yield, e.g., a composite dark-matter candidate with a magnetic moment.

Results

Asymmetries in units of $\mathrm{Im}\,[g_V(c_5/M^2)]\,[\mathrm{MeV}^{-2}]$.

$\omega_{\rm min}$(MeV)	$\mathcal{A}^{\rm HHH}(n)$	BR(n)	$\mathcal{A}^{\rm HHH}(^{19}\mathrm{Ne})$	BR$(^{19}\mathrm{Ne})$
0.01	-5.61×10^{-3}	3.45×10^{-3}	-3.60×10^{-2}	4.82×10^{-2}
0.05	-1.30×10^{-2}	1.41×10^{-3}	-6.13×10^{-2}	2.82×10^{-2}
0.1	-2.20×10^{-2}	7.19×10^{-4}	-8.46×10^{-2}	2.01×10^{-2}
0.3	-5.34×10^{-2}	8.60×10^{-5}	-0.165	8.86×10^{-3}

Electromagnetic Simulation of T-Odd Effects

We first compute $\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}}$ and then the asymmetry. We work in $\mathcal{O}(\alpha)$ and in **leading recoil order**.

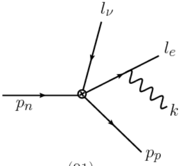
$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{tree}}|^2 + \mathcal{M}_{\mathrm{tree}} \cdot \mathcal{M}^*_{\mathrm{loop}} + \mathcal{M}_{\mathrm{loop}} \cdot \mathcal{M}^*_{\mathrm{tree}} + \mathcal{O}(\alpha^2)$$

$$\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}} \equiv \frac{1}{2} \sum_{\mathrm{spins}} |\mathcal{M}|^2_{\mathrm{T-odd}} = \frac{1}{2} \sum_{\mathrm{spins}} (2\mathrm{Re}(\mathcal{M}_{\mathrm{tree}} i \mathrm{Im} \mathcal{M}^*_{\mathrm{loop}}))$$

Note “Cutkosky cuts” [Cutkosky, 1960]

$$\mathrm{Im}(\mathcal{M}_{\mathrm{loop}}) = \frac{1}{8\pi^2} \sum_n \int d\rho_n \sum_{s_n} \mathcal{M}_{fn} \mathcal{M}^*_{in} = \frac{1}{8\pi^2} \int d\rho_n \sum_{s_n} \mathcal{M}_{fn} \mathcal{M}_{ni}$$

There are many cancellations. At tree level



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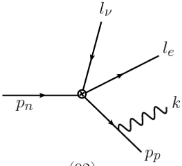
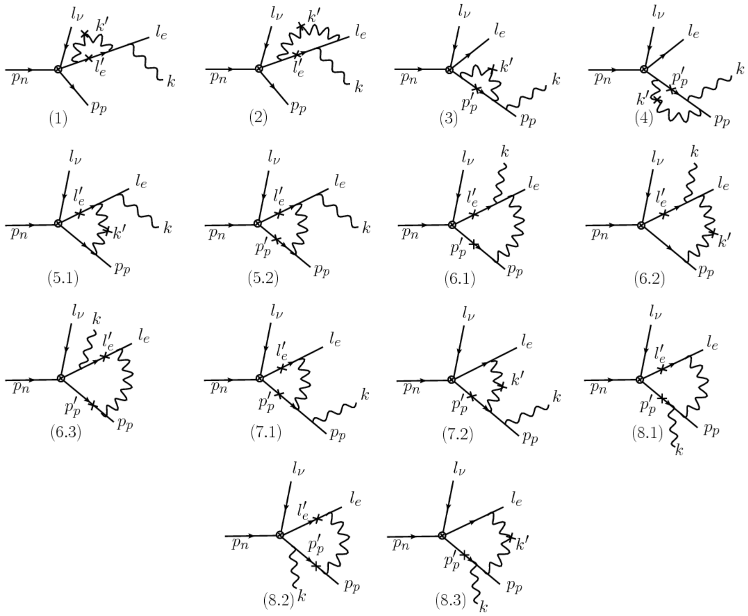


(02)

The Family of Two-Particle Cuts in $\mathcal{O}(e^3)$



Results

Table: Asymmetries from SM FSI in various weak decays. The range of the opening angle between the outgoing electron and photon is chosen to be $-0.9 < \cos(\theta_{e\gamma}) < 0.9$.

$\omega_{\rm min}$(MeV)	$\mathcal{A}^{\rm FSI}(n)$	$\mathcal{A}^{\rm FSI}(^{19}{\rm Ne})$	$\mathcal{A}^{\rm FSI}(^{35}{\rm Ar})$
0.01	1.76×10^{-5}	-2.86×10^{-5}	-8.35×10^{-4}
0.05	3.86×10^{-5}	-4.76×10^{-5}	-1.26×10^{-3}
0.1	6.07×10^{-5}	-6.40×10^{-5}	-1.60×10^{-3}
0.3	1.31×10^{-4}	-1.14×10^{-4}	-2.55×10^{-3}

The SM asymmetries are sufficiently small as to be negligible for present purposes.

Asymmetric Dark Matter: Experimental Signatures

ADM models can give distinctive collider signatures.

E.g. long-lived metastable states, new charged states at the weak scale, and/or colored states at a TeV.

Direct detection signals can arise from the interactions which i) eliminate the symmetric DM component or ii) transfer the asymmetry.

The latter can be realized through magnetic moment or charge radius couplings.

Both interactions can give rise to anomalous nuclear recoils....

[Bagnasco, Dine, and Thomas, PLB 1994; Barger, Keung, Marfatia, arXiv:1007.4345; Banks, Fortin, and Thomas, arXiv:1007.5515]

The models we consider can generate EDM signals within the reach of planned experiments.

[Hall, March-Russell, and West, arXiv:1010.0245]

A magnetic Faraday effect can also discover dark matter if it possesses a magnetic moment... and establish asymmetric dark matter.

[SG, 2008, 2009]

Summary and Outlook

Emergent new physics at low-energies is possible.

Low-energy probes of CP violation such as decay correlations and EDMs can be sensitive discriminants of such possibilities.

Many models of new physics give rise to sizeable EDMs!

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