Prospects for Resolving the Puzzle of the Missing Antimatter*

Susan Gardner
Department of Physics and Astronomy
University of Kentucky
Lexington, KY

*with thanks to H. R. Quinn (2003)
A Matter-Dominated Universe

[http://www.nasa.gov/vision/universe/starsgalaxies/wmap_pol.html]
A Cosmic Baryon Asymmetry (BAU)

Assessments in two different epochs agree!

Big-Bang Nucleosynthesis (BBN)

“α, β, γ” Alpher, Bethe, Gamow, “The Origin of the Chemical Elements,” 1948

Lightest Elements are made in the Big-Bang, but prediction depends on the BAU

Cosmic Microwave Background (CMB)

Dicke, Peebles, Roll, & Wilkinson, 1965; Penzias & Wilson, 1965

Pattern of Acoustic Peaks reveals baryonic matter
A Cosmic Baryon Asymmetry

Planck best-fit

Enhanced by baryons

Figure 22.1: The abundances of $^4$He, D, $^3$He, and $^7$Li as predicted by the standard model of Big-Bang nucleosynthesis [14]. The bands show the 95% CL range. Boxes indicate the observed light element abundances (smaller boxes: $\pm 2\sigma$ statistical errors; larger boxes: $\pm 2\sigma$ statistical and systematic errors). The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN concordance range (both at 95% CL).
A Cosmic Baryon Asymmetry

By initial condition?

We interpret the CMB in terms of an inflationary model, so that this seems unlikely.

Observations of the CMB power spectrum constrain the ratio of tensor (gravitational wave) to scalar (density fluctuations) power

\[ r < 0.11 \text{ at } 95\% \text{ C.L.} \]

[Planck, 1303.5076, 2013]

This constrains the energy scale of inflation to

\[ E_I \lesssim 2 \times 10^{16} \text{ GeV} \]
A Cosmic Baryon Asymmetry

From particle physics?

Confronting the observed D/H abundance with big-bang nucleosynthesis yields a baryon asymmetry: [Steigman, 2012]

$$\eta = \frac{n_{\text{baryon}}}{n_{\text{photon}}} = (5.96 \pm 0.28) \times 10^{-10}$$

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]

“From S. Okubo’s effect [CPV]
At high temperature
A coat is tailored for the Universe
To fit its skewed shape” [A. Sakharov]

[http://www.aip.org/history/sakharov/cosmresp.htm]
On the Discrete Symmetries

C, P, T and all that

Weak interactions violate parity P

[Wu, Ambler, Hayward, Hoppes, Hudson, 1957]

Nature can distinguish L from R: \( \bar{\nu}_e \) is R-handed!

\[ \int_{60}^{60} \text{Co} (J=5) \quad \int_{60}^{60} \text{Ni}^* (J=4) \quad + \quad \vec{e}^- + \quad \bar{\nu}_e \]

Intensity: \( I_e(\theta) = 1 - \frac{\vec{J} \cdot \vec{p}_e}{E_e} \) odd under \( \vec{p}_e \rightarrow -\vec{p}_e \)

Monday, November 11, 13
On the Discrete Symmetries

C, P, T and all that

Under charge-conjugation C:

\[ \Gamma(\pi^- \rightarrow e^- \bar{\nu}_R) \rightarrow \Gamma(\pi^+ \rightarrow e^+ \nu_R) \]

Despite

\[ \Gamma(\pi^- \rightarrow e^- \bar{\nu}_R) \rightarrow \Gamma(\pi^+ \rightarrow e^+ \nu_R) \]

0 : C is violated

CP is also broken!

Under the CPT theorem time-reversal T is broken as well
On the Discrete Symmetries

Direct Observation of $T$ violation in the $B$ system via “quantum entanglement”

The Origin of the Baryon Asymmetry

Derives from physics beyond the standard model!

The Sakharov conditions require B, C, and CP violation to generate a baryon asymmetry - and nonequilibrium dynamics to avoid washout.

The SM score card

B? Yes, at high temperatures
C and CP? Yes, but CP is “special”
Non-equilibrium dynamics? No. (!)

The discovered Higgs particle is of 125 GeV in mass; lattice simulations of the electroweak phase transition is NOT of first-order. [e.g., Aoki, Csikor, Fodor, Ukawa, 1999]
CP violation in the SM

Observed effects appear through quark mixing under the weak interaction

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}
_{\text{weak}} = V_{\text{CKM}}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
_{\text{mass}};
\quad V_{\text{CKM}} =
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

Cabibbo-Kobayashi-Maskawa (CKM) has 4 parameters

\[
V_{\text{CKM}} =
\begin{pmatrix}
  1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
  -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
  A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
+ O(\lambda^4)
\]

[Wolfenstein, 1983]

Intergenerational quark mixing is suppressed!

Estimates of the baryon excess in the Standard Model are much too small., [Farrar & Shaposhnikov, 1993; Gavela et al., 1994; Huet & Sather, 1995.]

\[\eta < 10^{-26}\]

Why? The operative CP violation in the SM (CKM) is special: it appears only if quarks of the same charge all differ in mass.
Testing the CKM Paradigm

Flavor physics studies tell us that flavor and CP violation in CC processes are CKM-like ("Minimal Flavor Violation")

Lattice QCD plays a crucial role!

[p-value = 76.0%]

[Lattice QCD plays a crucial role!]

The Standard Model

Successful though it is, it leaves many questions unanswered.

E.g., it cannot explain dark matter or dark energy, and gravity is excluded by design.
Expected Physics BSM?

Models with weak scale supersymmetry (and especially the Minimally Supersymmetric Standard Model (MSSM)) have been very popular

Because they...

• can explain “why” the weak scale $M_Z, M_W$ is so much lower than the Planck scale

• can possess a dark-matter candidate

• can potentially explain the cosmic baryon asymmetry

• ...

But the predicted effects have not yet been seen....
“Fine Tuning” does occur in Nature
Perhaps at the weak scale also

\[
\begin{array}{c}
\frac{7.2747}{3\alpha} \\
\frac{7.6542}{0^+} \\
\frac{4.4389}{2^+} \\
\frac{7.3666}{\alpha + ^8\text{Be}}
\end{array}
\]

\[^{12}\text{C}\]

[Hoyle, 1953; Dunbar, Wenzel, Whaling, 1953]
Recipes for a Baryon Asymmetry?

A baryon asymmetry (BAU) could be generated in different ways, and various discovery experiments can give hints:

- The discovery of a EDM would speak to new CP phases (enter *electroweak baryogenesis*).
- The discovery of $0\nu\beta\beta$ decay would tell us that neutrinos are Majorana (enter *leptogenesis*).
- The discovery of $n\bar{n}$ oscillations would tell us that neutrons are Majorana (enter *leptogenesis*).
- The discovery of a DM asymmetry (possible thr. Faraday rotation) would tell us that DM carries “baryon” number (enter “darko”genesis) [SG, 2008, 2009].

But only EDMs are directly tied to weak scale new physics....
Two Paths to Discovery

via low energy, precision measurements of BSM physics

Make “null” tests of the breaking of SM symmetries

Enter tests of B-L, CP (*), ....

*e.g., EDMs, $A_{CP}$ in charm (Dalitz plot)

Confront nonzero quantities which can be computed precisely (or assessed) within the SM

Enter proton weak charge, muon g-2, beta decay correlations, ....

All probe new degrees of freedom, both visible and possibly “hidden”
Suppose new physics enters at an energy scale

\[ E > \Lambda \]

Then for \( E < \Lambda \) we can extend the SM as per

\[ \mathcal{L}_{\text{SM}} \rightarrow \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^{D-4}} O_i^D, \]

where the new operators have mass dimension \( D>4 \) and we impose \( SU(2)_L \times U(1) \) gauge invariance on the operator basis

If light neutrino exchange mediates \( 0\nu\beta\beta \) decay, then

\[ \Lambda \sim 10^{14-15} \text{ GeV} \quad \text{(Careful!)} \]
Searches for new sources of CP violation

To uncover the mechanism of the BAU

- A new opportunity to measure heavy atom EDMs (Project X, FRIB)
- An ultrasensitive neutron EDM experiment (ORNL)
- Axion sensitivity thr. induced, time-dep. EDMs [Graham & Rajendran, 2013; Budker et al., 2013]
Heavy atom EDMs

evade Schiff’s theorem through large $Z$, finite nuclear size, and octupole deformation

Permanent deformation makes the nucleus more “rigid” and the Schiff moment computation more robust and 1000x bigger than $^{199}$Hg (existing best atomic EDM limit)

A great opportunity thr. Project X!
[arXiv:1306.5009]
Triple Product Momentum Correlations

In radiative beta-decay one can form a $T$-odd correlation from momenta alone

This is a pseudo-$T$-odd observable, so that it can be mimicked by FSI, but these are computable up to recoil order terms [SG, Daheng He, 2012]

The interaction which generates it comes from the gauging of the WZW term under SM electroweak gauge invariance [Harvey, Hill, Hill, 2007, 2008]

A direct measurement which constrain the phase of this interaction from physics BSM, possibly from “strong” hidden sector interactions [SG, Daheng He, 2013]
Summary

We live in a Universe of Matter
(and of dark matter and energy)

The LHC has discovered a Higgs (like) boson
but no other new particles - as yet.

A diverse program of low-energy, precision experiments exist that may yet “downselect” the BAU mechanism

The game is afoot!
Backup Slides
The next-generation isotope facility, such as FRIB after upgrade or Project X, is expected to be exploited for slowing and trapping.

In Phase 1 & 2, a typical experimental run will use 1-10 mCi of Ra (mCi) 1-10 10
d(225Ra) (10^{-28} e-cm) 100 10 0.1-1
equiv. d(199Hg) (10^{-30} e-cm) 10 1 0.01-0.1

What is presently lacking is a source of francium intense enough to make measurements from an EDM measurement in an ODT can be controlled at the level of 10^{-4} (ODT) as first suggested in Ref. [128].

The scheme at Argonne is to measure the EDM of Ra and the highly relativistic atomic electrons. This favorable case is being studied at the Argonne National Laboratory.

A large eEDM experiment is underway to develop the SNS nEDM experiment with the goal of achieving a sensitivity equivalent of any eEDM experiment ever attempted. Magnetic fields that change synchronously are one of the main effects that can lead to first-order systematic effects.

The Project-X isotope separator scenario is projected to produce 1-2 orders of magnitude more than current facilities and provides a promising alternative to extracting rare-gas isotopes from the FRIB beam dump as indicated in Table 5.2.

### Table 5.2: Projected sensitivities for $^{221/223}$Ra compared to $^{199}$Hg

<table>
<thead>
<tr>
<th>Facility</th>
<th>TRIUMF-ISAC</th>
<th>FRIB ($^{223}$Th source)</th>
<th>Project X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate</td>
<td>$2.5 \times 10^7$ s$^{-1}$</td>
<td>$1 \times 10^9$ s$^{-1}$</td>
<td>$3 \times 10^{10}$ s$^{-1}$</td>
</tr>
<tr>
<td># atoms</td>
<td>$3.5 \times 10^{10}$ s$^{-1}$</td>
<td>$1.4 \times 10^{12}$ s$^{-1}$</td>
<td>$4.2 \times 10^{13}$ s$^{-1}$</td>
</tr>
<tr>
<td>EDM Sensitivity</td>
<td>$1.3 \times 10^{-27}$ e-cm</td>
<td>$2 \times 10^{-28}$ e-cm</td>
<td>$5 \times 10^{-29}$ e-cm</td>
</tr>
<tr>
<td>$^{199}$Hg equivalent</td>
<td>$1.3 \times 10^{-29}$ e-cm</td>
<td>$2 \times 10^{-30}$ e-cm</td>
<td>$5 \times 10^{-31}$ e-cm</td>
</tr>
</tbody>
</table>

### Table 5.3: Projected sensitivities for $^{225}$Ra and $^{199}$Hg equivalent for three scenarios

<table>
<thead>
<tr>
<th>Phase</th>
<th>Phase 1 Phase 2 (upgrade) FRIB after upgrade, Project X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ra (mCi)</td>
<td>1-10 10 &gt; 1000</td>
</tr>
<tr>
<td>d($^{225}$Ra) (10^{-28} e-cm)</td>
<td>100 10 0.1-1</td>
</tr>
<tr>
<td>equiv. d($^{199}$Hg) (10^{-30} e-cm)</td>
<td>10 1 0.01-0.1</td>
</tr>
</tbody>
</table>
Observational Evidence for Dark Matter ranges from “local” to cosmic scales

Galactic Rotation Curves: [e.g., from Begeman, Broeils, and Sanders, 1991]

The observed circular speed does not track the luminous mass.

Most of the cosmic energy budget is of an unknown form!
Direct Detection: Dark Matter “WIMPs”
[from cdms.berkeley.edu; note Drukier & Stodolsky, 1984; Goodman & Witten, 1985]

**Stellar Halo**
The Galaxy's sparse, faint halo of stars is roughly spherical, some 200 kiloparsecs across and only about $10^5$ solar masses. Stars in the outer halo are very old; those in the inner halo are slightly younger.

**Segue I**
Dwarf galaxy.

**Ursa Major II**
Dwarf galaxy.

**Dark-Matter Halo**
The Galaxy's largest component is roughly spherical, several hundred kiloparsecs across, about $10^{12}$ times the mass of the Sun — and completely invisible.

**Dwarf Galaxies**
The Large and Small Magellanic Clouds are the biggest known dwarf galaxies, which probably formed in the denser clumps of the dark-matter halo. About two dozen are known, including Segue 1, Ursa Major II and the Sagittarius dwarf.

**The Sun**

**Segue**
An astronomical object that is part of our galaxy.

**Bubbles**
Back-to-back jets of energy erupted from the Galaxy's central black hole some 10 million years ago, forming two bubbles of hot gas that extend about 7,600 parsecs above and below the galactic plane.

**The Big Picture**
Recent data are illuminating the Milky Way's structure, including its bright disk and the fainter features surrounding it.
Analysis Framework

The QCD Challenge

Some of the needed QCD input requires control of the non-perturbative regime.

Lattice-QCD can, does, and will play a crucial role in advancing BSM searches....

There are examples, however, where the lattice-QCD calculations are not yet good enough for experimental needs (beta decay), but work arounds exist.

$g_A$!
The axial vector coupling

\[ \frac{g_A}{g_V} \]

[Bhattacharya et al., arXiv:1306.5435]

In beta-decay we must fit for SM and BSM physics simultaneously

Resolving the limits of the V-A Law

Searching for S, T currents in beta-decay

\[ \mathcal{L}^{(\text{eff})} = \mathcal{L}_{\text{SM}} + \sum_i \frac{1}{\Lambda_i^2} O_i \rightarrow \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_i^2} \sum_i \hat{\alpha}_i O_i, \quad \text{with} \quad \hat{\alpha}_i = \frac{v^2}{\Lambda_i^2}, \]

[Buchmuller & Wyler, 1986; Grzadkowski et al., 2010; Cirigliano, Gonzalez-Alonso, Graesser, 2010]

\[ \mathcal{L}_{\text{CC}} = -\frac{G_{\text{F}}^{(0)} V_{ud}}{\sqrt{2}} \left[ \left( 1 + \delta_\beta \right) \bar{\nu}_e \gamma_\mu (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma_\mu (1 - \gamma_5) d \right. \]
\[ + \epsilon_L \bar{\nu}_e \gamma_\mu (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma_\mu (1 - \gamma_5) d + \bar{\epsilon}_L \bar{\nu}_e \gamma_\mu (1 + \gamma_5) \nu_e \cdot \bar{u} \gamma_\mu (1 - \gamma_5) d \]
\[ + \epsilon_R \bar{\nu}_e \gamma_\mu (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma_\mu (1 + \gamma_5) d + \bar{\epsilon}_R \bar{\nu}_e \gamma_\mu (1 + \gamma_5) \nu_e \cdot \bar{u} \gamma_\mu (1 + \gamma_5) d \]
\[ + \epsilon_S \bar{\nu}_e (1 - \gamma_5) \nu_e \cdot \bar{u} d + \bar{\epsilon}_S \bar{\nu}_e (1 + \gamma_5) \nu_e \cdot \bar{u} d \]
\[ - \epsilon_P \bar{\nu}_e (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma_5 d - \bar{\epsilon}_P \bar{\nu}_e (1 + \gamma_5) \nu_e \cdot \bar{u} \gamma_5 d \]
\[ + \epsilon_T \bar{\nu}_e \sigma_{\mu\nu} (1 - \gamma_5) \nu_e \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d + \bar{\epsilon}_T \bar{\nu}_e \sigma_{\mu\nu} (1 + \gamma_5) \nu_e \cdot \bar{u} \sigma^{\mu\nu} (1 + \gamma_5) d + \text{h.c.} . \]

There is a one-to-one map between these operators and Lee & Yang, 1956
Resolving the limits of the V-A Law

Connecting to Lee & Yang

\[ \langle p(p_p) | \bar{u} \gamma_\mu d | n(p_n) \rangle = \bar{u}_p(p_p) \left[ g_V(q^2) \gamma_\mu - i \frac{\tilde{g}_T(V)(q^2)}{2M_N} \sigma_{\mu\nu}q^\nu + \frac{\tilde{g}_S(q^2)}{2M_N} q_\mu \right] u_n(p_n) \]

\[ \langle p(p_p) | \bar{u} \gamma_5 \gamma_\mu d | n(p_n) \rangle = \bar{u}_p(p_p) \left[ g_A(q^2) \gamma_\mu - i \frac{\tilde{g}_T(A)(q^2)}{2M_N} \sigma_{\mu\nu}q^\nu + \frac{\tilde{g}_P(q^2)}{2M_N} q_\mu \right] \gamma_5 u_n(p_n) \]

\[ \langle p(p_p) | \bar{u} d | n(p_n) \rangle = g_s(q^2) \bar{u}_p(p_p) u_n(p_n) \]

\[ \langle p(p_p) | \bar{u} \gamma_5 d | n(p_n) \rangle = g_P(q^2) \bar{u}_p(p_p) \gamma_5 u_n(p_n) \]

\[ \langle p(p_p) | \bar{u} \sigma_{\mu\nu} d | n(p_n) \rangle = \bar{u}_p(p_p) \left[ g_T(q^2) \sigma_{\mu\nu} + g_T^{(1)}(q^2) (q_\mu \gamma_\nu - q_\nu \gamma_\mu) \right. \]
\[ \left. + g_T^{(2)}(q^2) (q_\mu P_\nu - q_\nu P_\mu) + g_T^{(3)}(q^2) (\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu) \right] u_n(p_n) \]

Recently the scalar and tensor matrix elements have been computed in lattice-QCD [Bhattacharya et al., 1110.6448]

\[ \tilde{C}_S = g_S(\epsilon_S + \tilde{\epsilon}_S) , \]

\[ \tilde{C}_S' = g_S(\epsilon_S - \tilde{\epsilon}_S) , \]

\[ \tilde{C}_T = 4g_T(\epsilon_T + \tilde{\epsilon}_T) , \]

\[ \tilde{C}_T' = 4g_T(\epsilon_T - \tilde{\epsilon}_T) , \]
Resolving the limits of the V-A Law

\[
\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 \xi \\
\times \left[ 1 + b \frac{m_e}{E_e} + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} \\
+ \langle \vec{\sigma}_n \rangle \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]
\]

\[
\Xi = 1 + 3\lambda^2 + (g_S \epsilon_S)^2 + 3(4g_T \epsilon_T)^2,
\]

\[
a_0 = \frac{(1 - \lambda^2) - (g_S \epsilon_S)^2 + (4g_T \epsilon_T)^2}{(1 + 3\lambda^2) + (g_S \epsilon_S)^2 + 3(4g_T \epsilon_T)^2},
\]

\[
b_{\text{BSM}} = \frac{2(g_S \epsilon_S) - 6\lambda(4g_T \epsilon_T)}{(1 + 3\lambda^2) + (g_S \epsilon_S)^2 + 3(4g_T \epsilon_T)^2},
\]

\[
a_{\text{exp}} \equiv \frac{N(\cos \theta_{e\nu} > 0) - N(\cos \theta_{e\nu} < 0)}{N(\cos \theta_{e\nu} > 0) + N(\cos \theta_{e\nu} < 0)}
= \frac{1}{2} \beta \frac{a_1}{1 + b_{\text{BSM}} \frac{m_e}{E_e} + \frac{1}{3} a_2 \beta^2},
\]

\[
A_{\text{exp}} \equiv \frac{N(\cos \theta_e > 0) - N(\cos \theta_e < 0)}{N(\cos \theta_e > 0) + N(\cos \theta_e < 0)}
= \frac{1}{2} \beta \frac{A}{1 + b_{\text{BSM}} \frac{m_e}{E_e}}.
\]