FLAVOR PHYSICS – THEORETICAL ISSUES

J. Rosner – DPF 2013, UC Santa Cruz – August 15, 2013

Masses and mixings of quarks and leptons – pattern?

Status of mixings

Apparent suppression of new flavor-changing effects

New measurements of CP violation in heavy quark decays

Present and proposed measurements to advance that goal

Forthcoming $g - 2$ measurements

Forthcoming $\mu \to e$ conversion and $\mu \to e\gamma$ searches

What do we expect to learn from electric dipole moments?

The elephant in the room: Dark Matter

We know it exists (galaxies, clusters, structure, Bullet Cluster, . . .)

Five times as much of it as ordinary matter

Like trying to guess the structure of the periodic table knowing only Li, Be, and their relatives

QUARK MIXINGS

From CKMfitter (ICHEP 2012):

$$V_{CKM} = \begin{bmatrix} 0.974 & 0.225 & 0.0035e^{-i(68^\circ)} \\ -0.225 & 0.973 & 0.041 \\ 0.0085e^{-i(22^\circ)} & -0.040 & 0.999 \end{bmatrix}$$

Hierarchical! Correlation with quark masses?

$V_{us} \simeq \sqrt{m_d/m_s}$, $V_{cb} \simeq m_s/m_b$ noted long ago

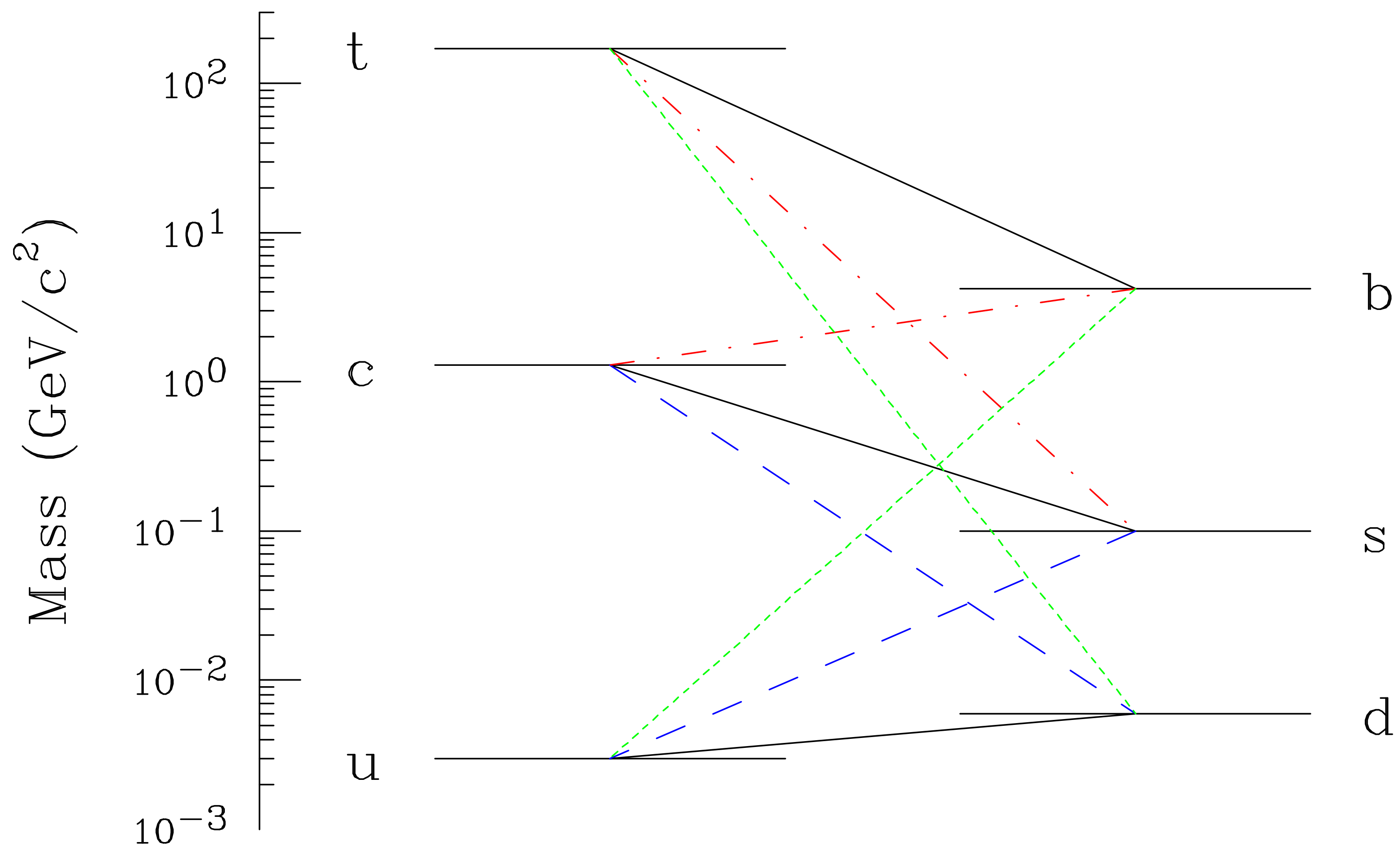
Underlying dynamics?

Possibly sensitive to logarithms of quark masses

Randall-Sundrum models: Position along fifth dimension

Mixing could be related to proximity in fifth dimension

QUARK MASSES



Lines: Charge-changing weak transitions

Black: $\mathcal{O}(1)$ Blue: 0.2 Red: 0.04 Green: < 0.01

LEPTON MIXINGS

Fogli *et al.*, PR D **86**, 013012 (2012):

$$U_{PMNS} = \begin{bmatrix} 0.82 & 0.55 & 0.155e^{-i\delta} \\ -0.44 - 0.08e^{i\delta} & 0.65 - 0.05e^{i\delta} & 0.61 \\ 0.35 - 0.10e^{i\delta} & -0.52 - 0.07e^{i\delta} & 0.78 \end{bmatrix}$$

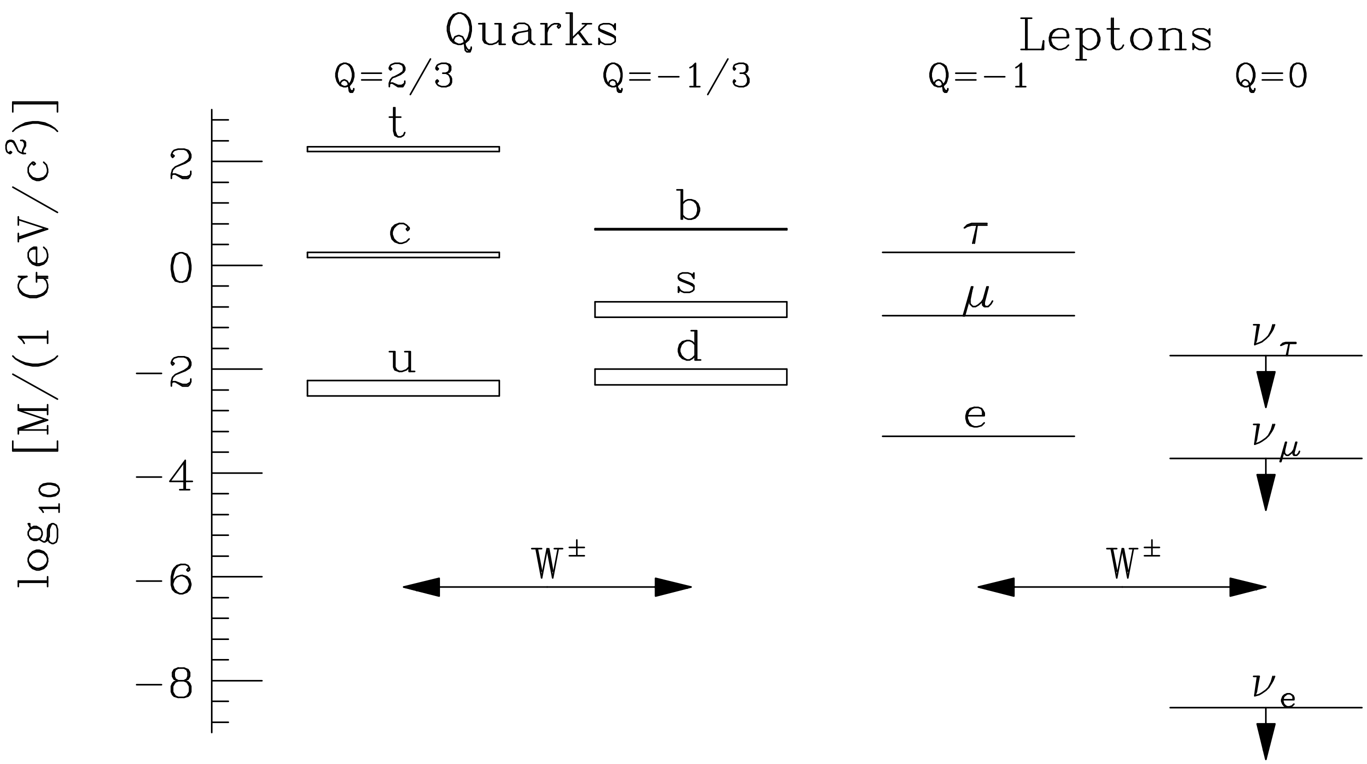
"Democratic" (aside from 13 element); not far from

$$\begin{bmatrix} 2/\sqrt{6} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{bmatrix} = \begin{bmatrix} 0.82 & 0.58 & 0 \\ -0.41 & 0.58 & 0.71 \\ 0.41 & -0.58 & 0.71 \end{bmatrix}$$

With sign change of last row, "tribimaximal" mixing (columns are eigenvectors of matrix with all 1's)

LEPTONS VS. QUARKS

What's different about neutrinos? Seesaw mechanism?



Consider difference between U_{PMNS} and tribimaximal U

All elements are $< \mathcal{O}(0.1)$ in magnitude

Suggests one look for tribimaximal mixing as a first approximation [Babu + , PR D72, 115003; McKeen + , PR D76, 073014]

FLAVOR-CHANGE SUPPRESSION

Take a page from Glashow-Iliopoulos-Maiani mechanism

- Without the charm quark, neutral current had flavor-changing parts
- Introduction of charm (quark-lepton analogy) canceled FCNC
- Definite predictions for loop-induced FCNC, e.g., in $K^+ \to \pi^+ \nu \bar{\nu}$

Tree-level FCNC in many new physics (NP) scenarios

- "Minimal flavor violation" (arXiv:1202.0464) sidesteps the problem
- Otherwise must assume NP scale is very large (e.g., $> 10^5$ TeV)
- As A. Pais used to say: "Where's the joke?"

Loop-induced FCNC: can $\neq$ SM but correlations exist

- $\Gamma(B_s \to \ell^+\ell^-)/\Gamma(B_d \to \ell^+\ell^-) = |V_{ts}/V_{td}|^2 \simeq 34$
- SM: $\mathcal{B}(B_s \to \ell^+\ell^-) = (3.7 \pm 0.4) \times 10^{-9}$, $\mathcal{B}(B_d \to \ell^+\ell^-) = (1.1 \pm 0.15) \times 10^{-10}$
- CMS: $\mathcal{B}(B_s \to \ell^+\ell^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$, $\mathcal{B}(B_d \to \ell^+\ell^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$
- SM: $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \simeq 8.5 \times 10^{-11}$, $\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) \simeq 2.4 \times 10^{-11}$,
  Correlated in MFV scenario (Bob Bernstein's talk)

CPV IN HEAVY QUARK DECAYS

Are A_{CP} in $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$ anomalous?

B. Bhattacharya, M. Gronau, JLR, PR D **87**, 074002 (2013), ...

CDF, Belle, LHCb: possible fractional-% asymmetries

Enhanced CPV $c \to u$ penguin $\Rightarrow$ CPV in other SCS charm decays such as $D^0 \to \pi^0\pi^0$, $D^+ \to \bar{K}^0\pi^+$

Can shift γ from $B \to DK$ by up to several degrees

Large A_{CP} in three-body B decays to charged hadrons

LHCb, arXiv:1306.1246; Bhattacharya, Gronau, JLR, 1306.2625

Large asymmetries in restricted regions of Dalitz plot, e.g.:

$$A_{CP}(B^+ \to \pi^+(\pi^+\pi^-)_{\mathrm{low}\,m}) = +0.622 \pm 0.075 \pm 0.032 \pm 0.007\ ,$$
$$A_{CP}(B^+ \to \pi^+(K^+K^-)_{\mathrm{low}\,m}) = -0.671 \pm 0.067 \pm 0.028 \pm 0.007\ .$$

SM tree and penguin amplitudes interfere; FSI important

U-spin, $\pi\pi \leftrightarrow K\bar{K}$ rescattering, and CPT play a role

MUON MAGNETIC MOMENT

Historical remarks on flavor-diagonal processes

Cabibbo current in an SU(2): neutral component changes flavor

Adding charm quark suppresses flavor-changing neutral current

Neutrino neutral current interactions as weak as they could be!

Merits/curiosities of the muon's anomalous moment a_μ

Numbers from PDG 2012 review (A. Hoecker and W. Marciano):

Exp–Th $= (287)(63)(49) \times 10^{-11}$, to be compared with:

Electroweak: $154(1)(2) \times 10^{-11}$, light-by-light (70 to 140) $\times 10^{-11}$;

$$a_\mu^{\rm SUSY} \simeq \pm 130 \times 10^{-11} \left(\frac{100 \text{ GeV}}{m_{\rm SUSY}}\right)^2 \tan\beta$$

which has to be larger than the electroweak term!

Where else do we see such sensitivity to SUSY?! The moral is:

Flavor-diagonal processes are unique windows to new physics!

MUON TO ELECTRON TRANSITIONS

Historical remarks

In 1962, two-neutrino discovery suppressed $\mu \to e\gamma$

Otherwise (Feinberg), $\mathcal{B}(\mu \to e\gamma) = \mathcal{O}(10^{-4})$

G. Jungman and I noted restrictive nature of $\mu \to e$ transitions: PL B **277**, 177 (1992): "rates comparable to or within a few orders of magnitude of current rate limits" from TeV-scale physics

Present situation (deGouvea, Vogel, 1303.4097)

Light-neutrino mixing:

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M_W^2} \right|^2 < 10^{-54} \,.$$

Your favorite mixings, Δm^2, $M_W^2 \to \Lambda^2$ easily exceed present limits

Dipole operator ($\mu \to e\gamma$) and 4-fermion contact term ($\bar{\mu} e \bar{q} q \Rightarrow$ conversion in Al) limit scale $\Lambda > 10^3$ TeV at present

$\mathcal{B}_{\mu \to e} < 7 \times 10^{-13}$ (present) $\to 10^{-16} \Rightarrow \Lambda \times 7$ for contact term

ELECTRIC DIPOLE MOMENTS

SM contributions small (Filippone 2009; Hewett 2013)

Hadrons: If $\bar{\theta} = 0$, CKM contributions need to involve all three quark families; $d_n \simeq 10^{-31 \text{ to } -32} e \cdot \text{cm}$ (three loops)

^{199}Hg: $d \simeq 10^{-33} e \cdot \text{cm}$ (heavy!)

Leptons: $d_e \simeq 10^{-39\pm1} e \cdot \text{cm}$ in standard model (four loops!)

Present status and prospects

Neutron: $d_n < 2.9 \times 10^{-26}$, factor of ~ 100 lower in five years

^{199}Hg: $d < 10^{-27} e \cdot \text{cm}$, factor of 10^5 lower by ???

Electron: Using cold molecules (e.g., YbF), large amplification: $d_e < 1.05 \times 10^{-27} e \cdot \text{cm}$; factor of 10^4 lower by ???

Remarks:

Many models beyond SM $\Rightarrow$ observable effects if CPV phase $\neq 0$

Example: CPV in $h \to \gamma\gamma$ (McKeen, Pospelov, Ritz, 1208.4597)

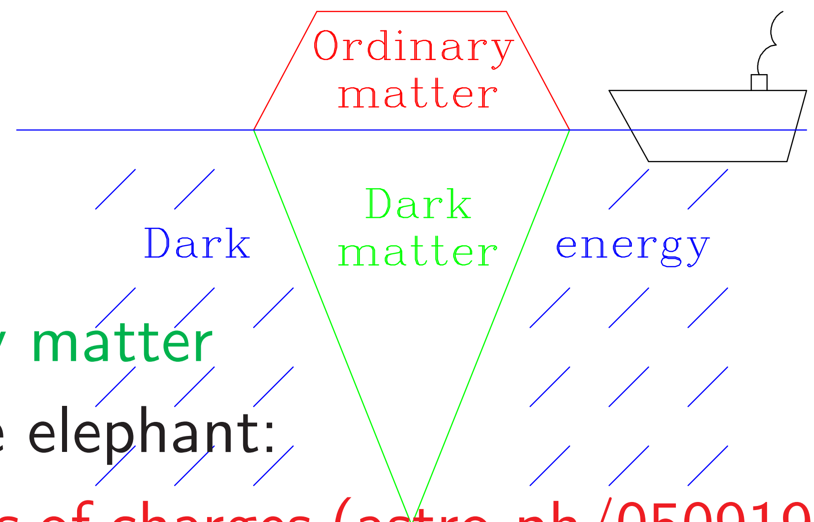
DARK MATTER: THE ELEPHANT

Relevance to the flavor problem

We may be privileged to see only a small subset of gauge interactions

Possible: A gauge sector G with its own "exotic" charges

Tip of the iceberg:
ordinary quarks and leptons $\Rightarrow$



Unseen part of the iceberg: $\Rightarrow$
could be clue to nature of ordinary matter

Blind men *do* have evidence of the elephant:

Some particles may have both types of charges (astro-ph/0509196):

Type of matter	Std. Model	G	Example(s)
Ordinary	Non-singlet	Singlet	Quarks, leptons
Mixed	Non-singlet	Non-singlet	Superpartners
Hidden	Singlet	Non-singlet	E'_8 of $E_8 \otimes E'_8$

HIDDEN SECTOR AND HIGGS

Higgs: a different tip of the same iceberg?

Light mass of Higgs: Higgs sector is not a replay of QCD $\times 2650$!

Nonetheless, composite Higgs theories refuse to die

$q\bar{q}$ composites in QCD: Lightest states are pseudoscalar

Higgs is $J^P = 0^+$; upper bounds on 0^- admixture are improving

Possible non-vector-like interaction between fermions?

Questions for Higgs and hidden sector

If Higgs is composite: One doublet or two?

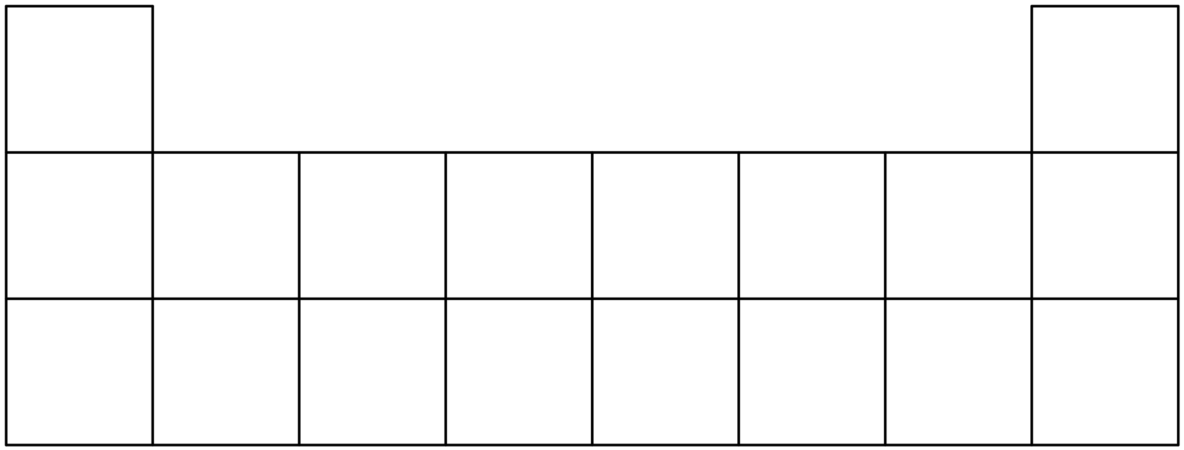
Do Higgs, quarks, and leptons share $Q = \pm 1/2$ components? E.g,

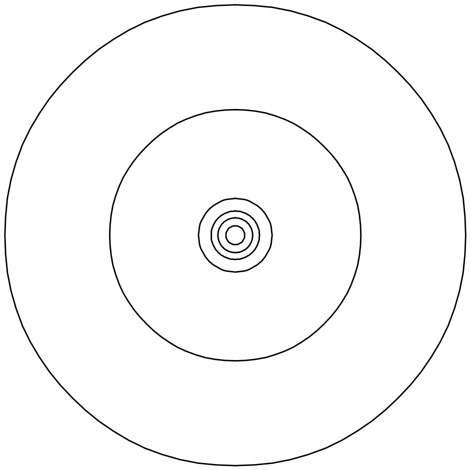
O. W. Greenberg + J. Sucher, PL B **99**, 339 (1981);

H. Fritzsch + G. Mandelbaum, PL B **102**, 319 (1981); **109**, 224

Does the hidden sector play a role in generating a composite Higgs?

TWO FAMILIAR PATTERNS





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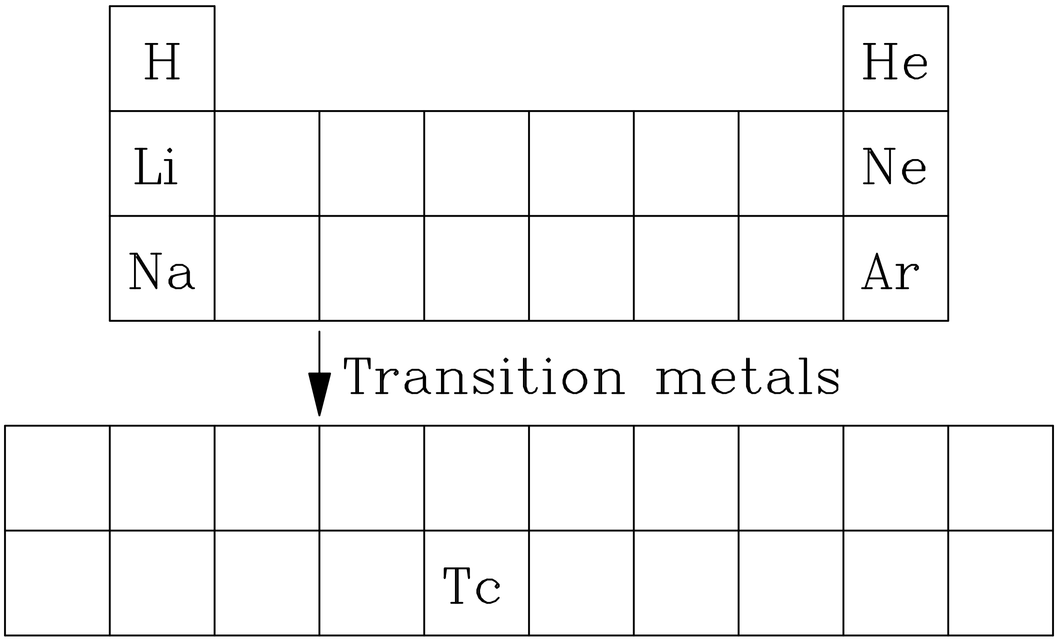

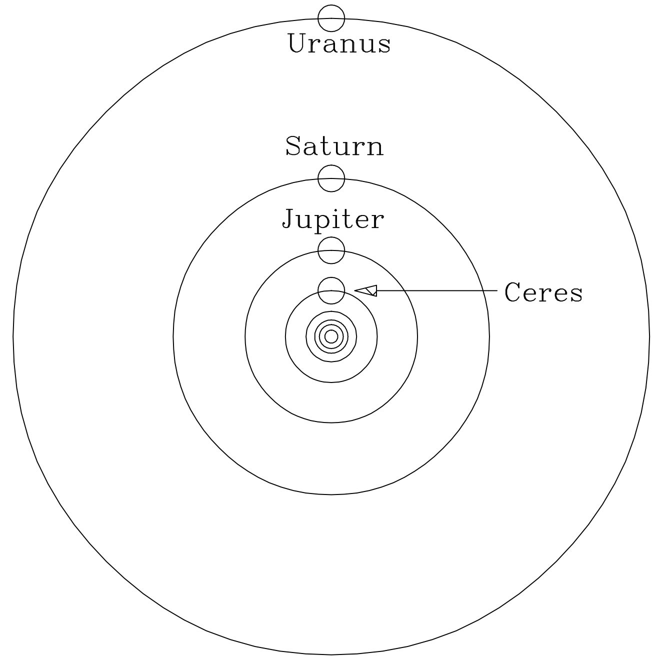

Periodic Table of the Elements

Planetary orbits

Each element has a different nuclear charge; electron shell structure governs chemistry; existience of Technetium predicted

Titius/Bode: $a(\mathrm{AU}) = 0.4 + 0.3k$ where $k = 0, 1, 2, 4, 8, \ldots$ predicted orbits of Ceres, Uranus

Titius/Bode law failed to predict orbit of Neptune; Pluto approximately where Neptune should have been; other dwarf planets don't fit; no dynamical explanation

Simulations can give similar relations; $\Leftrightarrow$ "anarchy" in quark-lepton masses.

CONCLUSIONS

Quarks and leptons: Periodic table or Titius-Bode?

So far, no convincing theory

Some useful differences between quarks and leptons

Further progress awaits better neutrino mixing measurements (including CP phase), improved understanding of the Higgs sector, and elucidation of the dark sector: What is hidden from us?

We are in a happy situation I have not seen since the '60's, when we really didn't know what was going on, but it didn't stop us from making progress!