Part I
A Tiny Intro to Tiny Physics

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Feeling the Pain

• For 20 years, a number of experimenters have made claims that electrochemistry can have “nuclear consequences” including inexplicable heat output, radiation, and new isotopes.

• Nearly all nuclear scientists view such claims with a level of disdain that can be difficult for non-physicists to understand.

• Why? What is the source of this disdain?
A Tiny Intro to Tiny Physics

• Goal: Not assertions, but understanding

• The mathematics can take years to learn...

• ... But the *concepts* are often much easier

• Understanding differences in scale, plus a few key analogies, can help explain why chemistry and nuclear physics are not easy to merge

• No math! But at the end, you should be able to solve a few simple quantum problems (!)
— Interlude 1 —
A Tale of Two Scales
First, the new Cowboys Stadium
Observations, and a Question

The new Cowboys Stadium encloses 104,000,000 cubic feet of air.

It can hold up to screaming 100,000 fans.
It covers 3 million square feet of area.

**Question:**
If Cowboys Stadium was a hydrogen atom (that is, 1 proton + 1 electron),
How big would the nucleus (proton) be?
Not *Everything* We Learned in Kindergarten is Right
A Tale of Scale:  **Scale 1 & Scale 2**

Here’s **Scale 1**, the **atom**:

Cowboys Stadium
104 million ft$^3$

Here’s **Scale 2**, the **nucleus**:

A large grain of sand, ~ 1/16 inch
Some “Weighty” Questions

Q: If the proton weighs as much as a sand grain, how much does the electron weigh?
A: About as much as a sand-grain volume of air

Q: How dense is an atom minus its proton?
A: (1) Take one sand-grain’s worth of air
   (2) Spread it out in all of Cowboy’s Stadium (!)
   (3) Answer: Thinner than a very good vacuum

To a proton, an atom looks like empty space
Interlude 2: Firefly Skip Rope!

Peter and Paul both find Elly very attractive.
Peter and Paul find each other very repulsive.
(Shh! Peter and Paul are also both a bit heavy.)
The Game Begins
Ellie flies everywhere in the loop!
She is so fast, she fills up the skip-rope loop like gas in a balloon!

Ellie discovers the loop always contains the *same* volume! It’s very small, so we’ll make up a name: one *Planck unit*.
Very long loops keep Ellie far away most of the time (P&P are sad!)
Very short loops also keep Ellie far away (and push *P&P way* too close to each other!)
A *just-right loop* keeps Peter and Paul as close to Ellie as possible.
Searching for Ellie

50% chance of finding Ellie

100% chance of finding Ellie
Energetic spinning gives two loops!

50% chance of finding Ellie

50% chance of finding Ellie

Note that clever Ellie somehow “tunnels” between loops
What if Peter and Paul were protons, and Ellie an electron?

• In that case... Ellie *really* likes to travel around!
• This is the **hydrogen molecular ion**, or **H$_2^+$**
• H$_2^+$ was the first quantum molecule calculated
Every wonder....

• If atoms are full of positive and negative electrical charges, why don’t they collapse?
• Why are atoms the size that they are?
• What’s all this about matter being “waves”?
• Why is “quantum physics” all probabilities?
• Can particles really be in two places at once?
• If so, have they been split into two parts?
• How do atoms and molecules bond?
What about multiple-loop cases?

- Adding a loop always requires faster twirling
- “Faster twirling” just means “adding energy”
- A one-loop **base state** is always lowest energy
- Multiple loops can store and give up energy
Skip Ropes & the Shapes of Atoms

“The z-axis p orbitals for shells n=2, 3, 4, and 5”

– An example of how electrons form distinct, precisely oriented structures in space

– All of chemistry depends on such structures!

*Note distorted resemblance to skip-rope loops*
Introducing a new player: Mary!

Peter and Paul find Mary as attractive as Ellie. Mary could be Ellie’s twin, except for one thing: Mary is about 200 times as heavy as Ellie!
Mary flies 200 times slower than Ellie, so her loop is 200 times smaller.

Peter, Paul, & Ellie: Nada!

Peter, Paul, & Mary: Close enough for the strong force to matter.
Bonding: Four Kinds of “Sticky”

• **Electrical**: “+” and “-” attract, “same” repels (male-female dating is not a bad analogy)

• **Strong**: Makes electrical look like a piker, but only applies over very short distances. The rules are weird (3 charges), but mostly the strong force is just very *sticky* at close range

• **Gravity**: Every thing attracts everything, but gravity is unbelievably, mind-bogglingly weak

• **Weak**: *Transforms* particles. Very, um, “weak.”
Muons = Really heavy electrons

• Isidor Isaac Rabi: “Who ordered that?” [as in from the lunch menu]. Mary is a muon

• Muons demonstrate a critical point:
  – Higher point-like mass means smaller waves
  – The critical phrase here is “point-like”

• Due to special relativity (covered later), muons are unstable and break down quickly

• Muons provide well-understood “cold fusion”
So when Mary drops by...?

• Nuclei almost always include another type of particle, neutrons, as well as protons

• A neutron is very similar to a proton, but has no charge (hence its name). They stick very easily to protons due to the strong force.

• If Peter, Paul, or both include a few neutrons, the neutrons make them more likely to stick

• Sticking—fusion—releases energy that dwarfs anything seen in the flimsy chemical domain
Why Not Use Muons, then?

• Their mass makes them unstable: Mary breaks down after a few rounds of cold fusions!

• Muon-based cold fusion was all the (classified) rage back around the 1950s, and had a small resurgence in the 1980s

• Muon fusion is like a cosmic joke on physicists: It comes right up to the line of producing usable energy... but no cajoling has ever made it cross that line, and options are very limited.
Can Particles Share the Same Wave?

- For electrons, the answer is yes... but only two!
- Two electrons can join a single “skip rope” as long as they look upside down to the other
- Additional newcomers must build new loops!
- Certain particles allow unlimited wave-joining
Quasiparticles: Tinker-toy particles

• Quantum mechanics allows group behaviors of particles to act very much like real particles

• Modern electronics, for examples, depend heavily on quasiparticles called holes that behave “almost” like positive electrons

• Superconductors are huge collections of quasiparticles that all share the same wave.

• Superconductor quasiparticles are large and delicate, so even modest heat destroys them
The real “cold fusion” problem

Here’s a hypothetical situation:

• Assume someone, somehow, figures out how to overcome the Ellie problem—that is, the inability of electrons to bring two protons into close contact. (Muons can actually do this!)

What happens next?

• A two-atom explosion that is the atomic-scale equivalent of setting off a hydrogen bomb inside a cozy little wooden shack. Boom!
Special Relativity (SR) in a Nutshell

**Rule 1:** If you move faster, you get heavier

**Rule 2:** If you move faster, your watch runs slower

**Rule 3:** You get shorter in the direction of motion

**Rule 4:** You can never reach the speed of light (c):
- You’d become more massive than the entire universe
- Your watch would come to a complete stop
- In the direction of motion, you’d be squashed infinitely thin

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**SR Slide Rule**

(a) \( \text{green} = \text{at rest mass or duration of 1 watch-second} \)

(b) \( \text{red} = \text{moving mass or duration of 1 watch-second} \)

(c) \( \frac{\text{green}}{\text{red}} = \text{length compression} \)

\( \theta = \text{speed expressed as an angle} = \arcsin(v/c); \text{ motionless} = 0^\circ, c = 90^\circ \)
Isn’t SR more complex than that?

Q: What happened to the equation E=mc²?
A: It’s implied by speed (energy) increasing mass

Q: What happened to gravity and curved space?
A: That’s general relativity, created 10 years later

Q: Isn’t every user view equally valid in SR?
A: Yes, but for energy-related experiments on earth (e.g. Stanford), the experimenter rules

Q: Doesn’t SR use hyperbolic Minkowski space?
A: Minkowski chose to use hyperbola. The SR Slide Rule is another view of the same equation
Quantum + SR = The Heart of Physics

• What happens when you combine Special Relativity with Quantum Mechanics?
• The answer: Just about everything that is of interest to anyone in particle physics
• Being able to add mass by adding velocity is like having cash to burn: You can use all that cash to buy—or build—whatever you want
• *Particle accelerators* are all about adding enough SR mass to create novel particles
The Foggy Reality Breakdown

• Having extra mass cuts both ways in SR: It can also abruptly turn back into velocity or energy

• This is why poor Mary the Muon is unstable

• Since Mary looks just like Ellie, only heavier, SR requires that Mary eventually shed that mass in the form of energy or other particles

• Only a handful of particles near the bottom of the energy ladder are able to survive this continual Foggy Reality Breakdown
Particle Debt Management

• What keeps the SR Foggy Reality Breakdown from destroying everything in the universe?
• The answer is unpaid debts. Particles aren’t allowed to keel over until they pay up in full!
• Electrons like Ellie, for example, have a debt of “borrowed” negative electrical charge
• Until electrons can fully cancel negative charge with opposing positive charge, they endure
• Debts are more often called conservation laws
A Tangled Web of Debts

• Why doesn’t the electron just cancel its debt with the nearest proton and be done with it?
• The answer that the proton also has other debts that are different from an electron
• Cancelling charge would just leave other debts unpaid for both the electron and proton
• The reason we exist at all is because of this complex, tangled web of deadlocked debts
• Antimatter exactly cancels all debts. Boom!
Is General Relativity (GR) Relevant?

• GR requires absolutely enormous masses or densities to become relevant to experiments

• Such masses cannot be created on earth

• Extremely high densities cannot be created easily because of quantum mechanics. Light particles “fluff up” and stay fuzzy (recall Ellie)

• Vacuum-like chemistry densities do not even approach nuclear densities, let alone GR ones

• GR is a very poor candidate for relevancy here
How about String Theory?

• The idea behind string theory is both simple and completely irrelevant to experimentation

• The idea is that deep down, electrons and other particle are small vibrating strings. Such vibrations can be thought of as languages

• Think of “the string vibrations” as similar to saying “the English language.” See a problem?

• String theory predicts nothing, requires near-infinite energies, & lacks experimental data
How about Dark Matter?

• Dark Matter is a fascinating and very real issue in modern astrophysics

• The idea is simple: The structure of galaxies indicates we can only see a tiny fraction of their real mass. The rest is “dark matter”

• Could this invisible dark matter particles provide energy in chemistry experiments?

• Very unlikely, since gravity tells us that dark matter density is very low in our solar system
How about Dark \textit{Energy}?

- Dark \textit{Energy} (not Matter) is a badly named but very interesting astrophysics concept.
- The concept of dark energy emerged because astronomy discovered something interesting: The Universe is exploding \textit{faster every day}.
- Dark energy is the name for “whatever” is pushing everything in the universe outward.
- Like dark matter, the density of dark energy in our solar system is low, else we’d see impacts.
Oddities and Unknowns

Mossbauer effect

• This well-studied effect uniquely bridges between nuclear energies (gamma rays) and single-wave collections of very low-energy quasiparticles called phonons. Phonons are essentially the quantum version of sound.

• No physicist in her or his right mind would have predicted Mossbauer. It was simply found, then explained via quantum theory.
Oddities and Unknowns

Fermi seas

• Look in a mirror if you want to see the rippling surface of a Fermi sea.

• Fermi seas are the opposite of shared-wave particles: Each added particle insists on its own wave, even if the wave requires more loops. “Surface” particles have the most loops.

• Electrons in metals form Fermi seas. It is their very hot Fermi surfaces that reflect light.
Oddities and Unknowns

Quantum vortices

• Rotation gets weird when waves are shared
• Quantum vortices are near-atomic-sized tubes that appear when a single-wave fluid rotates
• Fluid velocity in a quantum vortex nominally approaches infinity at the center of the vortex
• The atomicity of helium limits real velocity
• Richard Feynman predicted this phenomenon
Analytical Dangers and Traps

• Beware of relying *only* on mathematics!
  – Richard Feynman, warning of relying too much on the math of Maxwell’s Equations, quotes Dirac: “I understand what an equation means if I have way of figuring out the characteristics of its solution without actually solving it.”

• Beware even more of relying *only* on intuition!
  – Certainty is an *emotion*, just like fear or anger
  – Intuition without analytical follow-up is like driving based only on “a good hunch” of where the road is
Analytical Dangers and Traps

• Beware of letting hypotheses turn into dogmas
  – Science requires making difficult hypotheses
  – The scientific method: *Attack your own hypotheses*. The more ruthlessly you do it, the better.
  – Unexamined hypotheses become *de facto* miracles

• Beware of using knowledge to defend silliness
  – Any expert can intimidate outsiders, maybe insiders
  – Don’t decorate faulty reasoning with facts you know are irrelevant, but also intimidating to others
Analytical Dangers and Traps

• Last but by no means least:
  – Science is all about *reproducible* results. This cuts both ways:
    • If neither you nor anyone else can reproduce your claims, *they do not form a valid scientific hypothesis*
    • If strange claims are being replicated, **you must take them seriously**, no matter how distasteful they seem
  – Reproducibility also unavoidably involves *assessment of the groups and people involved*
    • I will address this in “Experiments in Search of a Theory”