Saturday Morning Physics 2007 at TAMU: Program Summary + Perspectives

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Outline

1.) Our Objectives
   • The Idea(s) behind, and Pillars of, the Program

2.) The Nuclear/Particle Micro-Cosmos
   • The Standard Model: Elementary Particles + Forces
   • The Strong Force: Quark Confinement, Mass Generation
     New Phases of Matter, Early Universe

3.) Nuclear/Particle Physics and the Universe
   • Gravity in Extremis: Black Holes and General Relativity
   • Dark Matter and beyond the Standard Model

4.) (Your) Perspectives
   • Expanding Your Knowledge; College, or even Physics as a Job?
1. Our Objectives

- Give high school students (teachers) the opportunity to learn about frontier science in Nuclear Physics
- Provide education
- Use understandable language
- Convey the excitement of ongoing research
- Dispel prejudices about Nuclear Physics
- Reveal perspectives for choosing university-physics study as (beginning of) career path
- Hands-on experience
- Have fun! (and donuts …)

1.2 Pillars of Saturday Morning Physics 2007

- Standard Model: matter particles, force types + carriers
  - R. Fries

- Modern Particle accelerators + detectors
  - C. Gagliardi

- Dark Matter in the cosmos, Supersymmetry and the neutralino
  - B. Dutta

- Heavy Quarks + Quark-Gluon Plasma Elephants in a Liquid
  - S. Mioduszewski

- Black Holes: Gravity, Equivalence Principle + Relativity
  - A. Belyanin

- The origin of mass, the dense vacuum, and its evaporation
  - H. van Hees

SMP ’07 Presentations
2.) The Discovery of the (Sub-) Atomic World

• **Rutherford’s α-scattering (1911):**
  - most of the atom is “empty space”
  - mass is concentrated in the atomic **nucleus**

• nucleus itself has structure:
  made of **protons (+), neutrons (0),**
  held together by “**strong**” **force**

• “Rutherford Scattering” 1968 (**SLAC**):
  yet smaller constituents in the proton
  → “**quarks**” and the **Strong Force**!

• 1984: **p-p** Scattering Exps. at **CERN**:
  discovery of heavy bosons
  → **W** and **Z**: **Weak-Force** carriers!

### 2.2. Particle Accelerators and Detectors

• probe the properties of particles and matter by exciting them
  ⇒ accelerate particles and collide them,
  interpret the reaction products (recall **Rutherford 1911**!)

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**Accelerate with Alternating Voltage**

**Bend Particles with Magnetic Fields**
2.3 The Standard Model of Elementary Particles

- based on symmetry principles:
  matter particles (fermions: half-integer spin)
  interact via force carriers (bosons: integer spin)
- stable matter: $u, d, e^-, \nu_e$
- 2 more “generations” (heavier + short-lived)

**Force Carriers and Strength**

<table>
<thead>
<tr>
<th>Force Carriers</th>
<th>Electromagnetic</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier</td>
<td>$W^+, W^-, Z^0$</td>
<td>Gluon</td>
</tr>
<tr>
<td>Acts on</td>
<td>Quarks and Leptons</td>
<td>Quarks and Gluons</td>
</tr>
</tbody>
</table>

2.4 Unsettled Problems of the Standard Model:

**Where do the particle masses come from?**

- 1. generation: “light” up/down quark, electron: $m_{u,d,e} \approx 0.5-5$ MeV/c²
- 2.+3. generation: medium/heavy weight ($m_{s,c,t} = 100-170,000$ MeV)

**Current Theoretical Prediction:**

**Higgs Boson** and Celebrity effect:

- Higgs Field condenses (lower energy) + fills all space (“symmetry breaking”)
  $<0|\phi|0> \neq 0$ **Higgs Condensate**
- elementary particles have to “plough” through “condensate” = mass!
- **Higgs Boson** not (yet?) discovered!
2.5 Unsettled Problems of the Strong Force

protons + neutrons made of 3 quarks:

\[ u \quad d \quad u \]

up/down quark: mass \( m_{u,d} \approx 5 \text{MeV}/c^2 \)

but: proton mass \( m_{p,n} = 940 \text{MeV}/c^2 \)

2 Mysteries of the Strong Force:

- How can we test the vacuum and >98% of the visible mass?
- Why are quarks not observed in isolation (Confinement)? rather “glued” together:

\[ F_s(r) = \text{const} \]

\[ \langle 0 | \bar{q} q | 0 \rangle \approx 5 \text{fm}^{-3} \]

The vacuum is very dense!

2.5.2 From Nuclei to the Quark-Gluon Plasma

Nuclear Matter dissolves into the Quark-Gluon Plasma (QGP):

- hadrons overlap, quarks are liberated \( \Rightarrow \) Deconfinement!!
- \( \langle \bar{q} q \rangle \) condensate “evaporates”, \( M_q \rightarrow m_q \) \( \Rightarrow \) Mass dissolves!!
- required temperature \( \approx 200 \text{MeV} \approx 4\cdot10^{12} \, \text{oK} \) (1μs after big bang)

How do we pump this enormous amount of energy into the vacuum??
Accelerate Gold-Nuclei to $100\text{GeV/nucleon}$ and collide them!

2.6 Recreating the “Little Bang” in the Laboratory

How to look for particles inside the matter?

- suppression of $J/\psi$ particles in QGP (deconfinement!)
- electron-positron decays of the $\rho(770)$-meson (mass!)

$\text{Au} + \text{Au} \rightarrow X$
2.7 J/ψ Suppression in the Quark-Gluon Plasma

**Theoretical Prediction:**

- J/ψ dissolves in the QGP
- If QGP is formed in Heavy-Ion Collision, J/ψ production should be suppressed
- quantify: “Nuclear Modification Factor”

\[ R_{AA} = \frac{J/\psi \text{ yield in Au-Au}}{J/\psi \text{ yield for p-p}} \]

- =1 no suppression
- < 1 suppression!

Suppression confirmed in CERN Exps.!

2.7.2 J/ψ at Higher Energies: RHIC Experiments

Central Au+Au at RHIC:
- very hot QGP ⇒ strong J/ψ suppression!
- but: ≈20 c\bar{c} pairs ⇒ regeneration c++\bar{c} → J/ψ

**Evidence for Regeneration of J/ψ in QGP?!**

**PHENIX J/ψ Data vs. Theory**
2.8 e^+e^- Spectra and the “Mass” Problem

- calculate $\rho \rightarrow e^+e^-$ decays in the “fireball”

Experimental data presently favor the “Melting” scenario

But what about the Gravitational Force?

- Irrelevant in the Microcosmos (!?!)  
- Essential in the Universe!
3. Gravity in Extremis: Black Holes

Objects so massive that not even light can escape!

Newtonian Mechanics:

\[ K = \frac{1}{2}mv^2, \quad U = -\frac{GMm}{R} \]

as mass increases, so does the gravitational pull

\[ K = |U| \quad \Rightarrow \quad v_{esc} = \sqrt{\frac{2GM}{R}} \quad \quad \quad \quad \quad \quad \quad v_{esc} = c \quad \Rightarrow \quad R_s = \frac{2GM}{c^2} \]

- Result **accidentally** correct!
- Newtonian Mechanics not applicable for speed close to \( c \)
- Need theory of special/general relativity!

3.1 Theory of General Relativity

- **Equivalence Principle:**
  The effect of the gravitational force in an inertial frame is equivalent to introducing an accelerated frame with no gravitational force

  \[ \Rightarrow \text{e.g., person in freely falling elevator does not feel gravitational force} \]

  \[ \Rightarrow \text{re-interpretation of gravity as a “geometric” effect!} \]
  \[ \Rightarrow \text{the presence of mass induces a “curvature” of space-time} \]
  \[ \Rightarrow \text{also light rays should experience: deflection, slowing down!] \]}
3.2 Experimental Verification of General Relativity

• Bending of Light from a Star through the Sun’s Gravity

Further Confirmations:
• Redshift of light when climbing out of gravitational field
• Precession of mercury’s orbit (long-standing discrepancy!)

3.3 Space-Time Singularities: Black Holes

If an object with given mass is contracted below its Schwarzschild radius, everything - even light - has not enough energy to escape!

⇒ The object is a space-time singularity, i.e. a Black Hole!!
3.4 Black Holes in the Universe

- Supermassive BHs in galactic centers (~$10^6 \, M_{\text{sun}}$)
- Collapse of massive star (~$10 \, M_{\text{sun}}$)
- Early Universe?

<table>
<thead>
<tr>
<th>Object</th>
<th>Mass ($M_\odot$)</th>
<th>$R_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star</td>
<td>10</td>
<td>30 km</td>
</tr>
<tr>
<td>Star</td>
<td>3</td>
<td>9 km</td>
</tr>
<tr>
<td>Star</td>
<td>2</td>
<td>6 km</td>
</tr>
<tr>
<td>Sun</td>
<td>1</td>
<td>3 km</td>
</tr>
<tr>
<td>Earth</td>
<td>0.000003</td>
<td>0.9 cm</td>
</tr>
</tbody>
</table>

But there is more “Invisible” Matter + Energy in the Universe
3.5 Evidence for Dark Matter

- motion of stars within galaxies: there must be more matter than we “see” (emits light)
  ⇒ Dark Matter:
    - “background”? 
    - new particles?

3.6 More Evidence + Dark Matter Properties

Cosmic collision of 2 galaxy clusters: DM unaffected!

The Dark Matter Sandwich:
- very weakly interacting
- charge-neutral
- slowly moving (“cold”)
- long-lived heavy particle
  ⇒ no such particle in the Standard Model!
  New idea needed!
3.7 Supersymmetry

- Standard-Model particles ↔ supersymmetric partners (fermion↔boson)
- Supersymmetry “broken”: $M_{\text{stand}} << M_{\text{super}} \sim 1\text{TeV/c}^2$
- one stable supersym. particle: neutralino (heavy, neutral)

3.8 How to Measure Dark Matter in the Lab?

- proton-proton collisions at the highest energy:
  Large Hadron Collider (LHC) at CERN:
4.) **Some Perspectives for You**

**If you**

- Enjoy / are excited by Physics / Science
- Tend to be curious
- Like to try things out AND/OR like math, computers

*then we recommend to:*

- Watch out for future SMP Series at A&M
- Consider enrolling in the Physics Undergraduate Program at A&M
- Inform yourself about future career paths in Physics

### 4.2 Future Plans for SMP at TAMU

- At least 3 more series planned (one per year; spring or fall?)
- Expand the coverage of forefront Nuclear Physics topics:
  - compact stellar objects (neutron stars, supernovae, gamma ray bursters, …)
  - nuclear astrophysics (formation of elements)
  - (quark-gluon) structure of hadrons + their interactions
  - nuclear structure, nuclear energy …
- New colleagues will join the Cyclotron this fall
- Connect to other SMP programs in the US and Europe (e.g. the heavy-ion research center (GSI) in Darmstadt, Germany)
- Extend to other fields in physics (Quantum Optics, Condensed Matter, …)
4.3 Physics as a Job (Passion?!)

Undergraduate Study (4 years)
REU programs / internships

PhD Program
5 years graduate study: courses + thesis on research project

Postdoctoral Research Associate
Broaden your research scope
Start becoming independent
3-8 years

Faculty Position at Research University
Build graduate program
Teach courses, administration
Supervise students+postdocs

Private Industry,
Banks, Research Labs,
School Teacher,
...

National Laboratories
Research Administration

5.) Thanks to:

- You! (students/participants)
- Our supporting high-school teachers!
- Our lecturers: Rainer Fries, Carl Gagliardi, Saskia Mioduszewski, Hendrik van Hees, Alexey Belyanin, Bhaskar Dutta
- The “technical” support team: Kendra Beasley, Shana Hutchins, Sharon Jeske, Bruce Hyman, Tony Ramirez, Robert Tribble (Cyclotron Director)
- The SMP organizing team (Daniel Cabrera, Hendrik van Hees, Lorenzo Ravagli, Xingbo Zhao)