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 …)
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
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 $\alpha$-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!)

Accumulate 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</th>
<th>Carried By</th>
<th>Acts on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>Graviton (not yet observed)</td>
<td>All</td>
</tr>
<tr>
<td>Weak (Electroweak)</td>
<td>( W^+, W^-, Z^0 )</td>
<td>Quarks and Leptons</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Photon</td>
<td>Quarks and Charged Leptons and ( W^+, W^- )</td>
</tr>
<tr>
<td>Strong</td>
<td>Gluon</td>
<td>Quarks and Gluons</td>
</tr>
</tbody>
</table>

\[ \alpha_{em} \approx 0.01 \]

\[ \alpha_s \approx 1 \]
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/c^2
- **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”)
  - $\langle 0|\phi|0 \rangle \neq 0$ 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:

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

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

Quark-antiquark pair condensate:
\( \langle 0 | \bar{q} q | 0 \rangle \approx 5 \text{fm}^{-3} \)
The vacuum is very dense!

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:

\[ F_s(r) = \text{const} \]
2.5.2 From Nuclei to the Quark-Gluon Plasma

Heat and evaporate the Vacuum!

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 \( \sim 200 \text{MeV} \approx 4 \cdot 10^{12} \, ^\circ\text{K} \) (1\( \mu \text{s} \) after big bang)

How do we pump this enormous amount of energy into the vacuum??
Answer: The Relativistic Heavy-Ion Collider!!

Accelerate Gold-Nuclei to $100\text{GeV/nucleon}$ and collide them!
2.6 Recreating the “Little Bang” in the Laboratory

Freeze-Out Hadron Gas

\[ \tau \approx 4 \cdot 10^{-23} \text{s} \]

QGP ?! (\( \tau \approx 2 \cdot 10^{-23} \text{s} \))

Au + Au → X

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!)
2.7 $J/\psi$ Suppression in the Quark-Gluon Plasma

**Theoretical Prediction:**

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

\[
R_{AA} = \frac{J/\psi \text{ yield in Au-Au}}{J/\psi \text{ yield for p-p}} \left\{ \begin{array}{c}
=1 \text{ no suppression} \\
< 1 \text{ suppression!}
\end{array} \right.
\]

Suppression confirmed in CERN Exps.!
2.7.2 $J/\psi$ at Higher Energies: RHIC Experiments

Central Au+Au at RHIC:

- very hot QGP $\Rightarrow$ strong $J/\psi$ suppression!
- but: $\sim 20$ $c\bar{c}$ pairs $\Rightarrow$ regeneration $c+\bar{c} \rightarrow J/\psi$

**Evidence for Regeneration of $J/\psi$ in QGP?!**

**PHENIX $J/\psi$ Data vs. Theory**

- Peripheral Collisions
- Central Collisions

Diagram showing the data comparison between PHENIX $J/\psi$ data and theoretical predictions.
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

\[ v_{esc} = \sqrt{\frac{2GM}{R}} \]

\[ v_{esc} = c \quad \Rightarrow \quad R_s = \frac{2GM}{c^2} \]

- 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

⇒ e.g., person in freely falling elevator does not feel gravitational force

⇒ re-interpretation of gravity as a “geometric” effect!
⇒ the presence of mass induces a “curvature” of space-time
⇒ 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

**General Relativity**: Einstein described gravity as a warping of space-time around a massive object. The stronger the gravity, the more space-time is warped.

\[
R_s = \frac{2GM}{c^2}
\]

If an object with given mass is contracted below it’s 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?

**Schwarzschild Radii**

<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>

**Our Galaxy**

Motion of stars close to BH!?

**Supernova 1987A**

Binary BH - star system?
But there is more “Invisible” Matter + Energy in the Universe

Today, I take you to the Dark Matter world.
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”: $M_{\text{stand}} \ll M_{\text{super}} \sim 1\text{TeV}/c^2$
- one stable supersym. particle: neutralino (heavy, neutral)

Dark Matter Candidate!
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)