Introduction to Nuclear and Particle Physics Directorate

Haiyan Gao

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Brief Introduction of myself

Tsinghua University (84-88) (BS)
California Institute of Technology (89-94) (Ph.D.)
Univ. of Illinois, Urbana-Champaign (94-96) (postdoc)
Argonne National Lab (96-97) (staff)
Massachusetts Institute of Technology (97-04)
Duke Univ. (02-present)
Duke Kunshan University (Jan 2015 – June 2019)
Brookhaven National Laboratory (June 2021 – )
Nuclear and Particle Physics

Our mission is to lead and support discovery-based, innovation-driven research at the frontiers of the subatomic world. We are world-leading in nuclear physics research, building and operating accelerator-based user facilities that serve international scientific communities. We also play a leading role in global particle physics programs that push the limits of precision and expand our understanding of the cosmos. Our pursuit of this fundamental and discovery research yields scientific and technological breakthroughs, and applications that benefit society—such as radioisotopes used to support industrial, medical and national security needs.

Our work draws on an international community filled with unique voices and perspectives, all contributing their ideas and experiences. We are passionate about welcoming people from all backgrounds and helping them succeed. Collectively, we will expand the boundaries of science and technology, advance the knowledge of humankind, bring new applications to society, and further our understanding of the natural world.

New NPP web page https://www.bnl.gov/npp
Fundamental forces in nature
The standard model of Particle Physics

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Mediators</th>
<th>Relative Strength</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>$g$</td>
<td>$10^{38}$</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>E&amp;M</td>
<td>$\gamma$</td>
<td>$10^{36}$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>Weak</td>
<td>$W, Z$</td>
<td>$10^{25}$</td>
<td>$10^{-18}$</td>
</tr>
<tr>
<td>Gravitation</td>
<td>gravitons</td>
<td>1</td>
<td>$\infty$</td>
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</tbody>
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SM very successful (no gravity)
New physics exists (neutrino mass, dark matter, baryon number asymmetry of the universe,....)
HEP: Energy, intensity, cosmic frontiers
NP: Fundamental symmetries and neutrinos, precision measurements

HEP: high-energy physics
NP: nuclear physics
High Energy Physics: Understanding the Origin of Space and Time

**ATLAS experiment (energy frontier)**
- Lead Lab for U.S. ATLAS collaboration of 800 U.S. scientists
- Leading US ATLAS Operations program and hosting ATLAS computing center

**Neutrino Program (intensity frontier)**
- Studying properties of neutrinos with MicroBooNE experiment
- Operating Proto-DUNE detector with BNL-developed cold electronics

**Belle II experiment (intensity frontier)**
- Lead Lab for U.S. Belle II experiment in Japan

**Rubin Observatory (cosmic frontier)**
- Commissioning the experiment in Chile
- Developing computing and software for data analysis

**Theory (all)**
- Developing new ideas and models in neutrino, collider, and precision particle physics

ATLAS published over 1000 papers

Exclusion of sterile neutrinos

Assembly of muon system at CERN

New ATLAS/Belle II computing center
High Energy Physics: Driving and Enabling the Future of the Field

Energy Frontier
• Hosting project office for $250M ATLAS upgrade
• Building magnets for the HL-LHC upgrade
• Developing computing and software for effective ATLAS data management

Intensity Frontier
• Key contributions to DUNE experiment
  • Leading DUNE Module 2 activities
• Planning studies of charge-parity violation with Belle II experiment

Cosmic Frontier
• Soon to analyze unique Rubin Observatory camera data
• Lead lab for LuSEE-Night mission to the far side of the moon
  • Detect “Dark Ages” signal from early Universe

Leading Technology Developments for Particle Physics
• Computing, software, detectors, and electronics
• Accelerator R&D, including superconducting magnets

Participating in long term planning at Snowmass
• Over 130 white papers with proposals submitted by BNL scientists
Natural physics – study of structure of matter in all its forms

- Most of the mass and energy in the universe around us comes from nuclei and nuclear reactions.
- The nucleus is a unique form of matter in that all the forces of nature are present: (strong, electromagnetic, weak).

About 1 second after the Big Bang, protons and neutrons are formed.

In today’s universe, 99% visible matter are atomic nuclei (protons and neutrons).
RHIC – a Unique Research Tool

• Heavy ion collisions
  • Explore new state of matter: Quark Gluon Plasma
  • Collide many different ion species

• Polarized proton collisions
  • Only collider of spin polarized protons to explore the internal spin structure of protons.
  • Gluons carry part of proton spin
Relativistic Heavy Ion Collider (RHIC) Complex

- Uniquely flexible and only hadron collider in the United States for exploration of QCD phase diagram and proton spin
- Injectors also used for application programs
  - Linac/BLIP for isotope production
  - Booster/NSRL for space radiation studies
  - Tandem for industrial/academic users
- R&D for future facilities and application (sources, cooling, pol. beams, …)
**NASA Space Radiation Laboratory (NSRL)**

- Started in 2003, simulates galactic radiation for human space flight
  - Heavy ion beams from AGS Booster
  - Electron Beam Ion Source (EBIS) provides all necessary ion beams
  - New laser ion source for EBIS allows for rapid species switching to simulate energy and species spectrum of deep space radiation field

- Additional uses of NSRL
  - Radiation effects studies (rapidly growing demand for satellite electronics testing)
  - R&D of ion beam cancer treatment
  - Agreement with NASA in place for non-NASA users (“non-designated user facility”)
**Brookhaven Linac Isotope Producer (BLIP)**

*50th anniversary*

- Target irradiation with 116 – 200 MeV, 160 mA proton beam
- Production of medical radio-isotopes for U.S.:
  - Mainly Sr-82, shared between LANL and BNL
  - R&D of new radio-isotopes for diagnosis and therapy (Ac-225, needs ~ 200 MeV protons)
- Significant expansion is underway:
  - BLIP target and proton beam intensity upgrades
  - Refurbishment of additional hot cells for Ac-225 processing
  - Bringing up a low-energy Cyclotron for supplying radionuclides currently available only from foreign suppliers, and an alternative Ac-225 production route with radium targets (Ac-225 without Ac-227 contamination)

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**Sr-82**: coronary artery disease diagnosis, used under rest and stress conditions

**Ac-225**: Alpha emitter for treatment of metastatic prostate cancer
Quark-gluon plasma as “perfect liquid” discovered at RHIC

The News of the QGP Hit the Streets

Universe May Have Begun as Liquid, Not Gas

Associated Press
Tuesday, April 19, 2005; Page A05

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have pervaded the first microseconds of existence.

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

by Mark Peploe
news@nature.com

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.

John Harris (Yale)

Early Universe was ‘liquid-like’

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.

The high-energy collisions probed open the nuclei to reveal their most basic particles, known as quarks and gluons.

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect “liquid”.

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.
There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: (1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.

LEReC = Low Energy RHIC electron Cooling
First-ever electron cooling with bunched beams
Test case for electron cooling at EIC

Beam Energy Scan
- What is the phase boundary of ordinary nuclear matter?
- Is there a critical point (e.g., liquid/vapor phases coexist for water) in the QCD phase diagram? If so, where?

BES-2 Completed as of June 7, 2021!
Completing the RHIC Mission with sPHENIX and STAR

- sPHENIX will use energetic probes (jets, heavy quarks) to study quark-gluon plasma with unprecedented precision
  - How the structureless "perfect" fluid emerges from the underlying interactions of quarks and gluons at high temperature
- State-of-the-art collider detector using technology developed for LHC by ONP and OHEP
- sPHENIX magnet and its hadron calorimeter could be part of the EIC project detector

- STAR with forward upgraded detectors ran successfully in Run 2022
  - 3-D tomography (like Magnetic Resonance Imaging) of the nucleon uncovers new information
- STAR exploits such 3-D parton dynamics in ways complementary to the EIC, where precision tomography of the nucleon and nuclei will be carried out

RHIC data taking scheduled for 2023–2025
sPHENIX upgrade and STAR with forward upgrade will fully utilize the enhanced (~50 times Au+Au design) luminosity of RHIC
2018 NAS Report: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the **mass** of the nucleon arise?
- How does the **spin** of the nucleon arise?
- What are the emergent properties of dense systems of gluons?
Proton Spin Puzzle

Proton spin (1/2) decomposition:
Quark spin only contributes a small fraction to the proton spin ~ 30%

Fermions: half-integer spins
Bosons: integer spins

Electron-Ion Collider
To be built at BNL
The Electron-Ion Collider

Recent IRA funding is a game changer!

**Project Design Goals**

- **High Luminosity:** \( L = 10^{33} - 10^{34} \text{cm}^{-2}\text{sec}^{-1}, \ 10 - 100 \ \text{fb}^{-1}/\text{year} \)
- **Highly Polarized Beams:** \( \sim 70\% \)
- **Large Center of Mass Energy Range:** \( E_{\text{cm}} = 20 - 140 \ \text{GeV} \)
- **Large Ion Species Range:** protons – Uranium
- **Large Detector Acceptance and Good Background Conditions**
- **Accommodate a Second Interaction Region (IR)**

Conceptual design scope and expected performance meet or exceed NSAC Long Range Plan (2015) and the EIC White Paper requirements endorsed by NAS (2018)

Major milestones:
- CD-0 December 2019; DOE EIC site (BNL) selection on Jan 9, 2020; CD-1 June 2021; EIC project detector reference design selected in March 2022; ePIC collaboration formed in July 2022

1362 collaborators, 36 countries, 267 institutions

Double Ring Design Based on Existing RHIC Facility

Brookhaven National Laboratory
Nuclear & Particle Physics at BNL

To understand sub-atomic world deeper and deeper

Develop unique technologies to answer fundamental questions in nature and applications of societal benefits

High-Energy Theory, Nuclear Physics Theory
Center for Fundamental Nuclear Science
RIKEN-BNL Research Center