Nuclear Physics

Questions, Directions, Applications

- Science Questions & Goals of Nuclear Physics
- Implications of Nuclear Physics for other Fields
- Applications of Nuclear Physics in other Fields
The Nuclear Chart

Proton: 2 up, 1 down quark
Neutron: 2 down, one up quark
Gluons: quark antiquark
Nucleus as a few-body system, interacting through the strong, weak, and electromagnetic forces!

Implications for: Astrophysics, Particle physics, Mesoscopic physics, Condensed matter physics

Applications in: Medicine, Material Science, Art and Archaeology, Geology and Climatology, Energy Production, Defense, Nuclear Forensics
Science Goals in Nuclear Physics

- Quark Structure of Nucleon
- Quark gluon plasma
- Nuclear Structure
- Nuclear Astrophysics
- Fundamental Studies
- Nuclear Physics Applications
The research aspect focuses on the use of the electromagnetic interaction to probe the structure of nucleons, few-nucleon systems, and complex nuclei.

- Quark structure & distribution in nucleons
- Quark confinement in nucleons
- Quark-gluon origin of nuclear spin (spin direction of up and down quarks)
- Charge distribution of the neutron (positive core and negative pion cloud)

Present facilities
- JLab, USA
- Desy, Germany
- Mami, Germany
- J-Parc, Japan
Phases of Nuclear Matter

QCD phase transitions in nuclear matter from quark structure of nuclei to quark gluon plasma. (from quark gluon liquid to quark gluon gas)

Measurements performed by the study of Relativistic Heavy Ion Collisions: RHIC

Collision creates the conditions of the early universe in a split second!
Accomplishments in Quark Gluon Plasmas

Starting the Relativistic Heavy Ion Collider program with BRAHMS, PHENIX, PHOBOS, and STAR

The quark gluon liquid or quark-gluon glass

Jet production in collision experiments

Lattice QCD calculations for QCD matter

nucleons $\Rightarrow$ quarks
**Future Goals & Efforts**

- Up-grade of PHENIX & STAR
- Increase of RHIC luminosity
- US participation in heavy ion program at LHC at CERN with the detectors ALICE
- Relativistic heavy ion beam experiments at FAIR/GSI
Nuclear Structure

From collective modes of excitation to probe the quantum structure and mean field model descriptions of the nucleus, to the study of drip-line behavior of the nucleus at the limits of stability; from structure of halo to super-heavy nuclei!
Rotations and Vibrations of a Liquid Drop

Rotations in the universe

- Centrifuge
- Water
- Hadrons
- Meson
- Neutron Stars
- Galaxies
- Galaxy Clusters
- Galaxies

Breathing Mode

GMR

Squeezing Mode

ISGDR
Matter far off Stability

- Nuclear Masses & decay properties
- Neutron halos
- Disappearance of shell structure
- Emergence of new shapes
- New collective modes of excitation
- Mapping the driplines
- Islands of stability

Neutron Star
Mass ~ 1.5 times the Sun
~12 miles in diameter

Solid crust
~1 mile thick

Heavy liquid interior
Mostly neutrons, with other particles
Accelerator Probes

United States
5 midsize university facilities
FSU, ND, TUNL, UoW, Yale
2 large university facilities,
TAMU, NSCL/MSU
2 national laboratory facilities
ATLAS/ANL, HIBRF/ORNL

International Community
Several universities
GANIL, France
GSI, Germany
INFN Legnaro, Italy
i-Themba, South Africa
Lanzhou, China
RCNP Osaka, Japan
RIKEN, Japan
Saha Institute, India
ISAC TRIUMF, Canada
Future Facilities

GI/SI/FAIR Germany (2015)

RIKEN, Japan (2008)

GANIL, France (2013)
FRIB at MSU

Construction has started, completion is scheduled for 2016
Neutrino Physics Accomplishments

Last decade opened new era of nuclear physics, the study of low energy neutrinos from sun and supernova and in laboratory decay

1998 Super Kamiokande (light water Cherenkov detector) announces evidence for neutrino oscillations which indicates that neutrinos have mass (0.05 – 0.18 eV)

2001 SNO (heavy water Cherenkov detector) confirmed neutrino oscillations and solves solar neutrino problem by detecting neutrinos consistent with predicted decay rate of $^8$B in the 3$^{rd}$ pp-chain

2003 KamLAND (liquid scintillator detector) confirmed neutrino oscillation from terrestrial neutrino source (reactor) and showed oscillation pattern

2007 Borexino (liquid scintillator detector) at Gran Sasso detects low energy solar neutrinos consistent with the predicted electron capture rate of $^7$Be in 2$^{nd}$ pp chain.
Fundamental Symmetries

Standard Model Initiative

What are the neutrino masses?
Tritium decay measurements with KATRIN

Are neutrinos their own antiparticles?
Neutrino less double beta decay measurements
In background free underground environments (Gran Sasso, SNO, WIPP, ...)

Violation of CP symmetry (matter anti-matter balance) by neutrino oscillation experiments and neutron EDM measurements (ultra-cold neutrons at Los Alamos, SNS, PSI, TRIUMF ...)

CUORE

MAJORANA

KATRIN

130Te

76Ge
designed for experiments that require extremely low cosmogenic backgrounds: in particular, the search for neutrino-less double beta decay and relic dark matter.
Nuclear Astrophysics

Understanding nuclear processes at the extreme temperature & density conditions of stellar environments!

- Stellar matter
- Stellar explosions
- White Dwarf matter
- Neutron Star matter
- Quark Star matter

Field requires close communication between nuclear experimentalists, theorists, stellar modelers and stellar observers (astronomers)
Nuclei are made in Stars

What the Big Bang made...

What we observe in early stars

What we find today

(The primordial abundance pattern)
Brian Fields (2002)

(The abundance pattern in the oldest observed stars He1017 & HH1327)
Anna Grebel (2006)

(The solar abundance pattern)
Measurements of solar reaction rates at LUNA, Gran Sasso within Gamow window of solar core temperature

Mapping the s-process at ORELA, LANSCE, n-ToF. Model simulations for AGB stars.

Probing reactions and decays far off stability for r- and rp-process at HRIBF and NSCL for supernovae and cataclysmic binaries.

Observation of r-process signatures in metal poor (old) halo stars

Mapping Galactic Radioactivity with gamma ray satellites
Astrophysics underground

Nuclear Reactions at stellar temperatures

- Timescale of stellar evolution
- Stellar energy production
- Nucleosynthesis from He to Fe
- Seed production for explosive nucleosynthesis
- Neutron production for trans-Fe elements
- Solar neutrino production

DIANA - two-Accelerator laboratory at DUSEL at the 4850 ft depth level.

Measurements handicapped by Cosmic Ray background
Astrophysics far off Stability

Study of nuclear reaction and decay processes far off stability for r-, ν-, rp-, vp, and p-process in cataclysmic binaries and/or supernova shock environments

Measurements at RIB facilities
International Situation

Roadmap for existing and planned underground laboratories with the size of the box corresponding to the relative space for experiments at each depth. These facilities are typically shared or primarily funded by other disciplines such as particle astrophysics.

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<tr>
<td>Rare Isotope Beams</td>
<td>Canada, CERN</td>
<td>ISAC I</td>
<td>ISOLDE</td>
<td>ISAC II</td>
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<tr>
<td>High Energy Heavy Ions</td>
<td>France, Germany, Japan, USA</td>
<td>GANIL/SPRAL</td>
<td>SPIRAL II</td>
<td>FAIR</td>
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The diagram illustrates the timeline and development of various facilities worldwide, highlighting the collaboration and shared funding across disciplines.