NUCLEAR PHYSICS APPLICATIONS
WITH EMPHASIS ON:

Instrumentation

Accelerators

Early Prospecting Gear

First Cyclotron, Berkeley Rad Lab

Lee S. Schroeder*

Presented to the Applications of Nuclear Science & Technology (ANS&T) Meeting
Rockville, Maryland, August 22-23, 2011
General Applications of Nuclear Physics
library.thinkquest.org/3471/general_applications.html - Cached
General applications of nuclear physics refers to both applications as a result of nuclear physics and applications which employ nuclear physics. ...

[PDF] Nuclear Physics Applications
isnap.nd.edu/Lectures/Junior_seminar/nuclear_physics_applications.pdf
File Format: PDF/Adobe Acrobat - Quick View
Nuclear Physics Applications in industry, medicine, and liberal arts. Energy Sources. Nuclear Forensics. Homeland Security. Imaging and Diagnostics ...

Nuclear physics - Wikipedia, the free encyclopedia
en.wikipedia.org/wiki/Nuclear_physics - Cached
Nuclear physics is the field of physics that studies the building blocks and interactions of atomic nuclei. The most commonly known applications of nuclear ...

New Trends in Nuclear Physics Applications and Technology
www2.pv.infn.it/~npdc19/ - Cached
May 4, 2006 – 19th Nuclear Physics Divisional Conference New Trends in Nuclear Physics Applications and Technology Pavia (Italy) September 5-9, 2005 ...

Nuclear Physics Applications
www.physics.carleton.ca/.../Physics/.../Physics/1008_Nuclear_Phys... - Cached
PHYS1008 Nuclear Physics Applications ... Nuclear reactions give out millions of eV/nucleus, and fission reactions take ~ 10-7s to occur. Catches: ...

Amazon.com: Nuclear Physics for Applications: A Model Approach ...
www.amazon.com › ... › Medical › Medicine › Internal Medicine - Cached
***** 1 review - $165.00 - In stock
Written by a researcher and teacher with experience at top institutes in the US and Europe, this textbook provides advanced undergraduates minor in ...
Nuclear Physics Applications
in industry, medicine, and liberal arts

- Energy Sources
- Nuclear Forensics
- Homeland Security
- Imaging and Diagnostics
- Radiation Treatment
- Material Science
- Art and Archaeology
Nuclear Energy R&D Roadmap

The Present: 2010 and Beyond Four Nuclear Energy Objectives
(The Road Map)

- Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors.
- Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration’s energy security and climate change goals.
- Develop sustainable fuel cycles.
- Understanding and minimizing the risks of nuclear proliferation and terrorism.
R&D Objective: Sustainable Fuel Cycles

Objectives
- In the near term, define and analyze fuel cycle technologies to develop options that increase the sustainability of nuclear energy
- In the medium term, select the preferred fuel cycle option(s) for further development
- By 2050, complete demonstration of the selected fuel cycle options at engineering scale and be ready to turn over to industry for commercialization

Necessary R&D
- Reduce transuranic production
- Implement science-based development program for fuel recycling
- Obtain mechanistic understanding of waste form behavior
- Perform fundamental analysis of fuel fabrication processes, and fuel/clad performance
- Evaluate very high burnup systems that require minimal or no chemical separations
- Develop transmutation systems needed to supplement partial recycling in thermal reactors
- Enable real time nuclear material accountancy and control
- Analyze storage and disposal system performance in a variety of environments
Science Based Approach to Nuclear Energy Development
The Road Map

- **Experiments** – Physical tests done to develop understanding of single effects or integrated system behaviors.

- **Theory** – Creation of models (i.e. theories) of physical behaviors based on understanding of fundamental scientific principals and/or experimental observations.

- **Modeling and Simulation** – Use of computational models to develop scientific understanding of the physical behaviors of systems. Also used to apply scientific understanding to predict the behavior of complex physical systems.

- **Demonstrations** – New technologies, regulatory frameworks, and business models integrated into first-of-kind system demonstrations that provide top-level validation of integrated system technical and financial performance.
Separations technologies are relevant to both front and back end nuclear fuel cycle technologies.
Advanced Test Reactor (ATR) at INL

- Material Testing (irradiations) Reactor since 1967
- Now National Scientific User Facility since April 2007
- Test Materials, Nuclear Fuels, and Instruments that Operate in Reactors
MANTRA: Measurement of Actinide Neutron Transmutation Rate by AMS

- Integral information on actinide neutron cross sections
- Joint INL/ANL project
  - Irradiate sample in ATR at INL
  - Evaluate yields in ATLAS/FMA at ANL
  - Expect sensitivities in $10^{-10} \rightarrow 10^{-12}$ range
Isotope spectrum at the FMA focal plane detector for a sample from the Joachimsthal mine – Measurement time ~ 10 min – $^{236}\text{U}/\text{U} \sim 1 \times 10^{-10}$

Example of a FMA Focal Plane Spectrum for $^{236}\text{U}$ AMS

$^{236}\text{U}$ cts (ion of interest)

$m/q = 236/39$

Ions with $m/q = 236/39 \pm \delta$

(structural material + cross-talk from previous runs + $^{235}\text{U}$)

(M. Paul, NIMB, B172, (2000) 688-692)
The Los Alamos Neutron Science Center (LANSCE)

Lujan Center  Weapons Neutron Research (WNR)  Isotope Production

Proton Radiography  UCN Experiment
Materials Test Station (MTS): Irradiate Transmutation Fuels and Materials in a Fast Neutron Spectrum

- The MTS will be driven by the 1-MW LANSCE proton beam, producing $10^{17}$ neutrons per second.
- System is deeply sub-critical, so there are no criticality concerns.
MTS flux level will be one-third to half of the world’s most intense research fast reactors.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Peak Fast Flux $\left(10^{15} \text{n/cm}^2/\text{s}\right)$</th>
<th>Peak Annual Fast Fluence* $\left(10^{22} \text{n/cm}^2/\text{y}\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTS (USA)</td>
<td>1.3</td>
<td>2.1</td>
</tr>
<tr>
<td>BOR-60 (Russia)</td>
<td>2.8</td>
<td>4.6</td>
</tr>
<tr>
<td>JOYO (Japan)</td>
<td>4.0</td>
<td>6.9</td>
</tr>
</tbody>
</table>

*Accounts for facility availability.
TPC’s in Nuclear Physics Today

STAR at RHIC
Au + Au
(0.1 + 0.1) TeV/n

ALICE at LHC
Pb + Pb
(1.38 + 1.38) TeV/n
Neutron Induced Fission Fragment Tracking Experiment

7 Universities
- Abilene Christian University
- Cal Poly San Luis Obispo
- Colorado School of Mines
- Georgia Institute of Technology
- Idaho State University
- Ohio University
- Oregon State University

4 National Labs
- Idaho National Laboratory
- Lawrence Livermore National Laboratory
- Los Alamos National Laboratory
- Pacific Northwest Laboratory
The Goal of NIFFTE

- Initiate a fission cross section measurement program to provide data of unprecedented precision.
- By applying TPC technology to these studies we anticipate making sub-1% uncertainty measurements.

Current $^{239}\text{Pu}(n,f)$ measurements

Spread in measurements leads to ~5% uncertainties in ENDF evaluations

±1% Uncertainties about ENDF evaluation
History of TPCs

- TPCs have been in use for about 30 years in high energy physics
  - Provide 3-D “pictures” of charged particle trajectories
- Miniaturization is the key to fission measurement implementation
  - Small volume and area constraints with high bandwidth requirements
  - Recent advances in computing and electronics enable this technique
NIFFTE TPC

• TPC will provide 3D “pictures” of the charged particle trajectories
  – Alpha backgrounds removed
  – Beam non-uniformities
  – Multi-actinide targets
  – H₂ drift gas will also minimize scattering

• TPC will use thin backing foils (<50 μg/cm²)
  – Minimize beam interaction backgrounds
  – Minimize multiple scattering of fragments
  – Alpha particle sample radiograph

• TPC will provide data on both fission fragments simultaneously
  – Random backgrounds removed (vertex requirement)
  – Fission vertex with <100 μm resolution (fission radiograph)
TPC at LANL

- The TPC installed at 90L at LANSCE
- 6 cards installed for first neutron beam test.
- Aug – Dec 2010
STAR at RHIC
Au + Au
(0.1 + 0.1) TeV/n

ALICE at LHC
Pb + Pb
(1.38 + 1.38) TeV/n

June 20, 2011
Nuclear Physics Working Group

N neutron
Induced Fission Fragment Tracking Experiment

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‡ Colorado School of Mines
‡ Georgia Institute of Technology
‡ Idaho State University
‡ Ohio University
‡ Oregon State University

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The Goal of NIFFTE
Uncertainties about ENDF evaluation
± 1%
Spread in measurements leads to ~5% uncertainties in ENDF evaluations

Traditional Method: Fission Chamber

Traditional Fission Chamber
± Operates on basic principles of ionization chamber
± Relatively simple, cheap and robust
± Count fission events (few words per event)
± Many systematic uncertainties folded together

† Target + beam non-

Fission Chamber
Simulated Charge Collection (one side of chamber)
Fission event counting remains one of largest uncertainties in the a lengthy list

New Method: Time Projection Chamber

Fission Time Projection Chamber

‡ ~2 words/event
‡ ~100 Hz rates
‡ 6000 channels @ 65 MHz is ~1 TB per second
‡ Fully reconstructed charged particle trajectories that include dE/dX information

Precision field cage
Segments anodes
Micromegas gas amplifier gap
Custom amplifiers
Custom waveform digitizers
Precision gas/temperature system
Advanced online monitoring
Advanced software

History of TPCs
† TPCs have been in use for about 30 years in high energy physics
± Provide 3-³SLFWXUHV´RIFKDUJHG particle trajectories
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± Multi-
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± Fission vertex with <100 m resolution (fission radiograph)

ADS for nuclear waste management
Beam optics & irradiation system development
Incineration strategies

Accelerator Driven Systems ADS
Single Event Effects in Electronics

initiated by a single charged particle

- **Direct ionization**
  - Charge deposit leads to upsets, transients, control failures, destructive failures
  - Energy transfer (LET) matters, not total energy
  - Dominant mechanism for Z>1 particles

- **Indirect ionization**
  - Primary particle scatters (fragments) lattice ion that then deposit charge
  - Interaction probability is energy-dependent
  - Upset probability depends on fragment LET
  - Dominant mechanism for proton SEE

Protons and heavier ions interact by BOTH mechanisms
Radiation Effects on Electronics

Single Event Effects (SEE)  
*caused by a single charged particle*

- “bitflips”, glitches, control failures
- Can include destructive burnout
- Energy transfer (LET), not total particle energy for direct ionization
- Proton SEEs are a secondary process
  - Energy *does* matter for nuclear interactions

Cumulative Exposure Effects  
*material structure changes over time*

- Total ionizing dose (TID)
  - *Transistors prefer ON or OFF*
- Displacement damage
  - *Increased leakage currents*
## US Heavy Ion SEE Facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Energy (MeV/n)</th>
<th>Ions</th>
<th>LET (MeV-cm²/mg)</th>
<th>Ion Range (μm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBNL</td>
<td>32</td>
<td>He-Ar</td>
<td>0.06-4.5</td>
<td>5560-690</td>
<td>1 m³ vacuum, 16 MeV/n in air 3.5” beam diameter 1x10⁶ ions/cm²/s, ~2000 hrs/yr</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>N-Kr</td>
<td>1.2-25</td>
<td>506-163</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>B-Xe</td>
<td>0.9-58</td>
<td>287-99</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>B-Bi</td>
<td>1.6-100</td>
<td>79-54</td>
<td></td>
</tr>
<tr>
<td>TAMU</td>
<td>40</td>
<td>Ne-Kr</td>
<td>1-14</td>
<td>1655-622</td>
<td>Air or vacuum, 1” beam diameter ~2000 hrs/yr Good range, slow ion changes</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>Ne-Xe</td>
<td>1.7-38</td>
<td>799-286</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Ne-Au</td>
<td>2.5-80</td>
<td>316-155</td>
<td></td>
</tr>
<tr>
<td>BNL</td>
<td>1-8</td>
<td>Li-Au</td>
<td>0.3-85</td>
<td>200-20</td>
<td>Many ions beyond Bragg peak SEU time limited, competes with AGS, RHIC, and NSRL</td>
</tr>
<tr>
<td>MSU</td>
<td>140</td>
<td>Kr</td>
<td>6.6</td>
<td>4500</td>
<td>SEU run once / 2-3 months Expensive, ~$2500/hr</td>
</tr>
<tr>
<td></td>
<td>123</td>
<td>Xe</td>
<td>14.7</td>
<td>3000</td>
<td></td>
</tr>
</tbody>
</table>

LBNL

- Fast ion changes – “cocktail” beams
- Protons available at same location
- 10-32 MeV neutron beams soon

TAMU

- Greater penetration range
- Higher LET coverage for given energy
- New science beams in 2011, SEU impact?
88-Inch Cyclotron Complex - Experimental Facilities
Began in 1995 with 10 MeV/u ions, limited list of beams

Added high energy series (15, 25, 40 & 55 MeV/u) over 1997-2005

Offered “in-air” testing in 2000 - usage hours increased from
~500/yr to ~2,500/yr

Usage by 1/3 Government/University and 2/3 Commercial agencies

Increase in international agencies in the past few years, mainly France.
<table>
<thead>
<tr>
<th>Testing Agencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actel Corporation</td>
</tr>
<tr>
<td>Aeroflex Corporation</td>
</tr>
<tr>
<td>Aerospace Corporation</td>
</tr>
<tr>
<td>Air Force</td>
</tr>
<tr>
<td>AMTEC Corporation</td>
</tr>
<tr>
<td>ASTRUM - France</td>
</tr>
<tr>
<td>ATK Mission Research</td>
</tr>
<tr>
<td>BAE Systems</td>
</tr>
<tr>
<td>Ball Aerospace</td>
</tr>
<tr>
<td>Boeing Corporation</td>
</tr>
<tr>
<td>Boeing Research &amp; Technology</td>
</tr>
<tr>
<td>Boeing Satellite Systems</td>
</tr>
<tr>
<td>Broadcom Communications</td>
</tr>
<tr>
<td>CAMBR / University of Idaho</td>
</tr>
<tr>
<td>CEA - France</td>
</tr>
<tr>
<td>Cisco Systems</td>
</tr>
<tr>
<td>Data Device Corporation</td>
</tr>
<tr>
<td>Full Circle Research</td>
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<tr>
<td>General Dynamics</td>
</tr>
<tr>
<td>Georgia Tech University</td>
</tr>
<tr>
<td>Harris Semiconductor</td>
</tr>
<tr>
<td>HIREX - France</td>
</tr>
<tr>
<td>Honeywell</td>
</tr>
<tr>
<td>Hughes Space Communications</td>
</tr>
<tr>
<td>IBM Corporation</td>
</tr>
<tr>
<td>ICS Radiation</td>
</tr>
<tr>
<td>Innovative Concepts, Incorporated</td>
</tr>
<tr>
<td>Intel Corporation</td>
</tr>
</tbody>
</table>
The Brookhaven Tandem Van de Graaff Facility

Ions for science and technology

Two large electrostatic Tandem Van de Graaff accelerators are part of the Relativistic Heavy Ion Collider and NASA Space Radiation Laboratory complex, injecting beams of ions into other accelerators for studies of the fundamental components of matter and their interactions and the effects of simulated space radiation. They also provide a large variety of ion beams to a community of high tech industrial and space applications users on a cost-recovery basis. Thus valuable services are provided while maintaining good operational continuity and adequate staffing levels.

The ion species available range from protons to gold, and the energies and intensities can be accurately controlled and continuously varied over many orders of magnitude. This unusual versatility results in applications that would otherwise be impossible or inconvenient.

Two main user applications of beams produced in the Tandems are the testing of critical space related hardware and the fabrication of ultra small-pore filter materials.

Simulated space radiation

Computers in space, and other instrument components, are susceptible to radiation damage and transient errors due to the impact of energetic ions — which do not reach us on Earth, where we are protected by the Earth’s atmosphere and magnetic field. The susceptibility of microchips to radiation has increased over the years as the size of the features shrinks to achieve increased computer power at reduced cost, weight, and power consumption.

The ions provided at the Brookhaven Tandem Facility enable users to test the radiation hardness of microchips and other materials under a wide variety of well-controlled conditions, which is essential for a detailed understanding and mitigation of the failures. For example, NASA used these beams to test some components of the Mars Rovers, one of which continues exploring that planet’s surface today after landing seven years ago.

Making very fine filters

There is only one method for fabricating filter materials with very uniform pores down to 50 nanometers, or billions of a meter, in diameter. Thin plastic films are irradiated with energetic heavy ions, and pores are developed later through preferential etching along the radiation-damaged tracks left behind by the ions.

The irradiation part of this procedure is carried out at the Brookhaven Tandem Facility in a unique irradiation chamber owned by the General Electric Corporation. There are very few similar facilities worldwide.

Alternative (but much less appealing) sources of ions used for this purpose are fission products produced inside a nuclear reactor. By using a particle accelerator such as the Tandem, material activation problems are avoided, parallel pores can be generated, and there is control over the ion species and energy, leading to better quality and wider range of products.

These fine-pore filters are used by the semiconductor industry to obtain particle-free water for rinsing silicon wafers; in medical and biological studies to separate microbes, viruses, and cells; and in other applications including filtration in the wine and beer industries.
Neutron Single Event Effects (SEE) are faults in electronic devices caused by neutrons from cosmic rays

- Neutrons are produced by cosmic rays in the upper atmosphere
- Neutrons have long mean-free paths so they penetrate to low altitudes
- Neutrons interact with Si and other elements in the device to produce charged particles
- Charged particles deposit charge in the sensitive volume which can cause the state of a node to change
- The neutron spectrum at WNR is similar to the neutron spectrum produced by cosmic rays in the atmosphere
- Industry can test their semiconductor parts by placing them in the WNR beam and measuring the failure rate with an acceleration factor of $\sim 10^7$
- 1 hour of testing at WNR is equivalent to several hundred years of use
Results of LANSCE/WNR measurements determine problem with ASCI Q-Machine

- The ASCI Q-Machine has 2048 nodes with a total of 8192 processors.
- During commissioning, it was observed that the Q-machine had a larger than expected failure rate. Approximately 20 fails / week (~3 fails / day).
- The question was whether this could be the result of neutron single-event upset.
- The system response was measured by putting one module of the Q-Machine in the LANSCE/WNR beam.
- Results of measurement accounted for approximately 80% of the failures. (IEEE Trans. Dev. Mat. Reliab. 5 2005)
- The failures were traced to a cache memory that was not error corrected.
- This result may have significant impact on future large computer systems.
Nuclear science instruments at LANSCE

- TPC, ionization chambers
- FIGARO \((n,xn+\gamma)\)
- DANCE (capture)
- \(N,Z \, (n, \text{charged particle})\)
- GEANIE \((n,x\gamma)\)
Proton Radiography (PRAD)

Explosive proton radiography experiments are conducted at the Los Alamos Neutron Science Center facility. In these experiments, a proton beam traveling inside a tube penetrates a target placed in a spherical vessel (left) to contain the explosion. Quadrupole magnets (orange) focus the scattered protons onto imaging detectors. This particular setup uses three imaging stations, including one installed in front of the target to examine the profile of the incoming proton beam. Collimators are located inside the beam tube.
Proton Radiography (PRAD)

Some experiments have investigated the hydrodynamic properties of shocked metal. (a) A 4-centimeter-diameter tin disk sits on a block of high explosive that is sandwiched between two layers of aluminum. (b) Some 10 microseconds following the blast, a radiograph reveals how the top aluminum plate is bent by the blast and how the tin falls apart from the explosive shock wave. The radiographs also reveal how gas and small chunks of matter intermix. (c) A computer simulation of the proton radiography experiment in (a) and (b).
Cosmic Ray Muon Tomography

The experimental apparatus
Pb + Automobile Engine

Photograph of the engine in the LMT

Mean scattering angle for a slice through the scene 50 cm above the base plate. The left panel shows the engine, the middle panel the engine plus the 10x10x 10 cm3 lead sample, and the right panel the difference.
NRF for Nuclear Materials Management

- Properties of NRF inspection
  - Identification of stable isotopes without sample preparation and destruction
  - Identification of isotopic content inside sealed containers
  - Identification of stable and radioactive isotopes behind shielding
  - Rapid isotopic identification

- Potential Applications
  - SNM: $^{235}$U, $^{239}$Pu and the power cycle actinides
  - MOX fuel pellets: ~ 3% HEU, country specific elements
  - Storage containers: 3013, 9975, 48Y, 30B
  - Fuel Reprocessing Waste products: technique and country specific
  - Reprocessed and Ore Refined SNM: technique and country specific
  - Nuclear Fuel cladding: Alloys specific to country and industry
    - Zircaloy alloy: Sn (USA), Nb (Russia), Others: Al, Ni, Cr, Fe, Ti and N.
  - Geographical fingerprints: O, C, Pb isotopes


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Actinide NRF Signatures

- Unambiguous signature for SNM isotopes and other Actinides
- NRF states in SNM < 3 MeV
The need for $^3$He-replacement technologies

<table>
<thead>
<tr>
<th>World $^3$He Applications</th>
<th>World demand (2009-2014):</th>
</tr>
</thead>
<tbody>
<tr>
<td>neuron scattering</td>
<td>~20 kliter/yr</td>
</tr>
<tr>
<td>*125 kliter needed from 2009-2015</td>
<td></td>
</tr>
<tr>
<td>security applications (US)</td>
<td>~22 kliter/yr</td>
</tr>
<tr>
<td>industrial, medical</td>
<td>~8 kliter/yr</td>
</tr>
<tr>
<td>(US)</td>
<td></td>
</tr>
<tr>
<td>safeguards (fission</td>
<td>~20 kliter/yr</td>
</tr>
<tr>
<td>counters)</td>
<td></td>
</tr>
<tr>
<td>DEMAND TOTAL:</td>
<td>~70 kliter/year</td>
</tr>
</tbody>
</table>

World $^3$He supply (2009-2014): in the short term $^3$He is only available from the US and Russia; the global supply total during this period as reported by the $^3$He supply crisis meeting, Munich July 2009 is SUPPLY TOTAL ~20 kliter/year.

World Short Fall → 50 kliter/year

Sources
- Helium detector expert group, "The $^3$He supply crisis and alternative techniques to $^3$He based neutron detectors for neutron scattering applications", proc. of meeting held at FRM II, Munich, July 2009.
Boron-coated Straw Detectors

$^{10}\text{B} + n \rightarrow \begin{cases} ^7\text{Li} + \alpha & 2.79\text{ MeV} \\ ^7\text{Li}^* + \alpha & 2.31\text{ MeV} \end{cases}$
Straw-based RPM

- A moderator block formed by bonding together long slabs of HDPE
- Long square grooves machined into each slab, to accommodate up to 171 straw detectors.
- Straws - 4 mm in diameter and 200 cm long
Replacement of $^3$He in Portable Field Applications

- Eleven detectors
  - 550 total straws
- High sensitivity
- Low weight
- Rugged
- High shock and vibration resistance

50-straw module with 100 cm long straws

1,864 miles round trip

Count Rate (cpm)

- Measured background rate
- Neutron flux geographical data

LBNL and Tech Source Inc.
Mission
To achieve a first-principles based understanding of the effect of irradiation-induced defects and microstructures on thermal transport in oxide nuclear fuels.

Achievements
Scientists at CMSNF are developing capabilities to link models that describe nanometer-sized phenomena to models that describe important physical properties in nuclear fuel. The specific nanometer-sized phenomena these models predict are the formation of defects in irradiated nuclear fuel. Key physical properties include the physical dimensions of a sample and the ability to transfer heat. Researchers at CMNSF have successfully developed a model that describes how nanometer-sized pockets empty of atoms, known as voids, are formed under irradiation and how these voids block heat flow, also known as phonon transport. Contrary to the previously held beliefs, CMSNF scientists discovered that the time evolution of the formation of voids during irradiation differs from the time evolution of the increase in material volume, known as swelling. From a heat transfer point of view, voids act to block the carriers of heat (phonons) in the material. CMSNF scientists are now investigating in greater detail how the voided spaces limit heat flow. These results may ultimately help improve the performance of fuel in nuclear reactors under normal and accident scenarios.
Swift Heavy Ion Irradiation

- Polycrystalline CeO$_2$
  - 3mm discs, 1mm thick
- Au ions
- Two energies:
  - 1GeV ± 120MeV
  - 300MeV ± 200MeV
- Fluences (ions/cm$^2$):
  - 5x$10^{10}$ ~ 5x$10^{12}$
- Room Temperature

UNILAC at GSI

120 m long accelerator at GSI
**Substructure:**

300 MeV, $5 \times 10^{10}$ ions/cm$^2$

- No apparent damage from ion tracks
- Low defect content

1 GeV, $5 \times 10^{12}$ ions/cm$^2$

- Ion track damage apparent
- Extensive number of recrystallized regions
Materials Science of Actinides
Energy Frontier Research Center

Nanoscale behavior
Thermochemistry
Synthesis
Computational Models
Applications

Complex Materials

Extreme Environments

Nanomaterials
Experimental Approach

Synchrotron Facilities:
APS, ALS, NSLS, CHESS

X-ray diffraction (XRD)
Infrared Spectroscopy (IR)

GSI Helmholtz Center for Heavy Ion Research Darmstadt, Germany

heavy ions: \(^{197}\text{Au}, \, ^{208}\text{Pb}, \, ^{238}\text{U}\)
kinetic energy: 2 – 50 GeV
energy loss: 10 – 55 keV/nm
ion dose: \(10^{13}\) ions/ cm\(^2\)

high-pressure irradiations ~50% c
ambient-pressure irradiations ~15% c
Combined Pressure & Irradiation in CeO$_2$

- Fluorite $\rightarrow$ Cotunnite
- Cotunnite $\rightarrow$ Cotunnite

7-GeV $^{238}$U
4$\times$10$^{12}$ ions/cm$^2$

- 20 GPa
- 60 GPa
Training the Next Generation of Innovators

The Office of Nuclear Physics within the Department of Energy’s (DOE) Office of Science has a long and productive partnership with universities and provides education opportunities and support to university professors and students associated with its basic nuclear physics research. This educational pipeline further fuels our economy through work in fields as diverse as national security, medicine, energy generation, space exploration, and more.

The pie chart above shows that many scientists who receive Ph.D.s in nuclear science go on to apply their knowledge working in professions outside the field after five to 10 years. Nuclear physics research facilities serve as training grounds for the next generation of scientists and engineers.

2004 survey data

The pie chart above shows that many scientists who receive Ph.D.s in nuclear science go on to apply their knowledge working in professions outside the field after five to 10 years. Nuclear physics research facilities serve as training grounds for the next generation of scientists and engineers.
Physics Applications

Energy
- ADS & Transmutation
- Fusion confinement
- Nuclear Waste
- Energy Storage

Nuclear Forensics
- Homeland Security
- Risk Assessments
- Nuclear Trafficking
- Proliferation

Life Science
- Medical Diagnostics
- Medical Therapy
- Radiobiology
- Biomedical tracers

Material Analysis
- Nanotechnology
- Ion Implantation
- Material Structure
- Geology & Climate
- Environment
- Art & Archaeology

Nuclear Defense
- Weapon Analysis
- Functionality
- Long-Term Storage

Computation
- Monte Carlo Simulation
- Network Simulation
- Software Development
- Quantum Computing
The GRETINA Spectrometer

- first-generation gamma-ray tracking detector
  - eff. > 5.4% @ 1.3MeV
  - P/T > 55% @ 1.3 MeV
- employs highly-segmented HPGe detectors enabling:
  - high energy resolution
  - position determination

\(^{137}\text{Cs pencil beam}\)
Tracking Procedure, Applications

- technology applicable to gamma-ray imaging applications:
  - location and identification of sources for verification, homeland security
  - medical imaging

- digitize segment signals
- locate interaction points by comparison to detector simulation
- group/order interaction points by best fit to Compton scattering formula
Nuclear Science

Expansion of the Universe

After the Big Bang, the universe expanded and cooled. At about 10^10 seconds, the universe was a soup of quarks, gluons, electrons, and neutrinos. As the temperature of the Universe, T Uruguay, cooled to about 10^3 K, this soup coalesced into protons, neutrons, and electrons. At time zero, some of the neutrons and protons formed helium, lithium, and helium nuclei. Still later, electrons combined with protons and these low-mass nuclei to form neutral atoms. Due to gravity, clouds of atoms contracted into stars, where hydrogen and helium fused into more massive chemical elements. Explosions that occurred from these massive elements then distanced them into space. The earth was formed from supernova debris.

Radioactivity

Radiation decay transforms a nucleus by emitting different particles. In alpha decay, the nucleus emits an alpha particle—a helium nucleus—and a gamma ray. In beta decay, the nucleus may emit an electron and antineutrino (or a positron and neutrino) to convert an atomic electron and extra energy to another nucleus. In a neutron, the nucleus is held together by the strong nuclear force, which is much stronger than the weak nuclear force. Nucleons (protons and neutrons) are the building blocks of the nucleus. Nucleons interact through the strong nuclear force, which is mediated by exchange of mesons—mesons are quarks that are exchanged during the strong interaction.

Nuclear Energy

Nuclear energy is the energy released when the bonds between the protons and neutrons in a nucleus are broken. This energy can be harnessed in nuclear reactions, which can release enormous amounts of energy. Nuclear reactions can be classified into two types: fission and fusion. Fission occurs when a large nucleus splits into two smaller nuclei, while fusion occurs when two smaller nuclei combine to form a larger nucleus.

Phases of Nuclear Matter

Nuclear matter can exist in several phases. In the early universe, protons and neutrons were the only stable particles. As the universe cooled, the strong nuclear force held the nuclei together, forming the first stars. At higher temperatures, quark-gluon plasma was created. This phase is characterized by the deconfinement of quarks and gluons, which are the fundamental particles of the strong nuclear force. In the early universe, the plasma was in a state of thermal equilibrium, with a temperature of about 10^14 K. As the universe cooled, the plasma gradually transformed into a state of hadrons, where quarks and gluons were confined and formed hadrons (protons and neutrons). The transition from the quark-gluon plasma to the hadron phase occurred gradually, and the process was not instantaneous. The transition from the quark-gluon plasma to the hadron phase is a complex process that involves the interplay of various forces and interactions between the particles.

Unstable Nuclei

Some nuclei are unstable and decay by emitting particles such as electrons, positrons, or neutrinos. This process is called radioactive decay. The rate at which a nucleus decays is determined by its half-life, which is the time it takes for half of the nuclei in a sample to decay. Nuclei with long half-lives are stable, while those with short half-lives are unstable and decay rapidly.

Chart of the Nuclides

The chart of the nuclides is a graph that shows the relationship between the atomic number (Z) and the mass number (A) of all known stable and unstable isotopes. The chart is divided into regions corresponding to the periodic table, with each region representing elements with similar properties. The chart also includes information on the stability of different isotopes and the processes that can cause them to decay.

Applications

Nuclear medicine is the use of radioactive substances to image and diagnose diseases. Radioactive substances can be used to trace the flow of blood or to detect the presence of specific molecular targets in the body. This information can be used to guide medical treatment and improve patient outcomes.

Space exploration

Nuclear energy is used in space exploration to power spacecraft and enable long-distance travel. Nuclear reactors are used to generate electrical power on board spacecraft, allowing them to communicate with Earth and perform scientific experiments. Nuclear energy is also used to power deep-space probes and to provide heating and cooling for onboard systems.

Magnetic resonance imaging

Magnetic resonance imaging (MRI) is a medical imaging technique that uses a strong magnetic field to produce detailed images of the body's internal structures. MRI uses radio waves to excite the nuclei of hydrogen atoms, which then emit signals that can be detected and used to create images of the body. MRI is widely used in medicine to diagnose and treat a variety of conditions, including tumors, infections, and structural abnormalities.
• Applications account for ~20-25% of the present Wall Chart

RECOMMEND

• Produce a separate Applications Wall Chart

• Have the Nuclear Science Community put it together along with the CPEP Organization
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BACKUP SLIDES
Nuclear Forensics
Role, State of the Art, and Program Needs
Joint Working Group of the American Physical Society
and the American Association for the Advancement of Science
The Fukushima Dai-ichi Nuclear Power Plant is located on the north-eastern coast of Japan in the Fukushima Prefecture.
Fukushima Dai-ichi Nuclear Power Plant (status before earthquake)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Power</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>460 MWe</td>
<td>Operating</td>
</tr>
<tr>
<td>2</td>
<td>784 MWe</td>
<td>Operating</td>
</tr>
<tr>
<td>3</td>
<td>784 MWe</td>
<td>Operating</td>
</tr>
<tr>
<td>4</td>
<td>784 MWe</td>
<td>Outage</td>
</tr>
<tr>
<td>5</td>
<td>784 MWe</td>
<td>Outage</td>
</tr>
<tr>
<td>6</td>
<td>1,100 MWe</td>
<td>Outage</td>
</tr>
</tbody>
</table>
Damage to Unit 1
Boiling Water Reactor
Officials vented steam to ease pressure buildup within reactor, and pumped more water to cool the fuel rods.

When the hydrogen-filled steam was vented, the hydrogen reacted with oxygen, either in the air or water outside the vessel, and exploded.

Containment vessel made of 15 centimetre thick stainless steel.

As temperatures rose, the zirconium cladding that makes up the fuel rod casings reacted with coolant water, becoming zirconium oxide and hydrogen.

Seawater being pumped in here to stop meltdown.

Reactor core with hot uranium fuel rods.