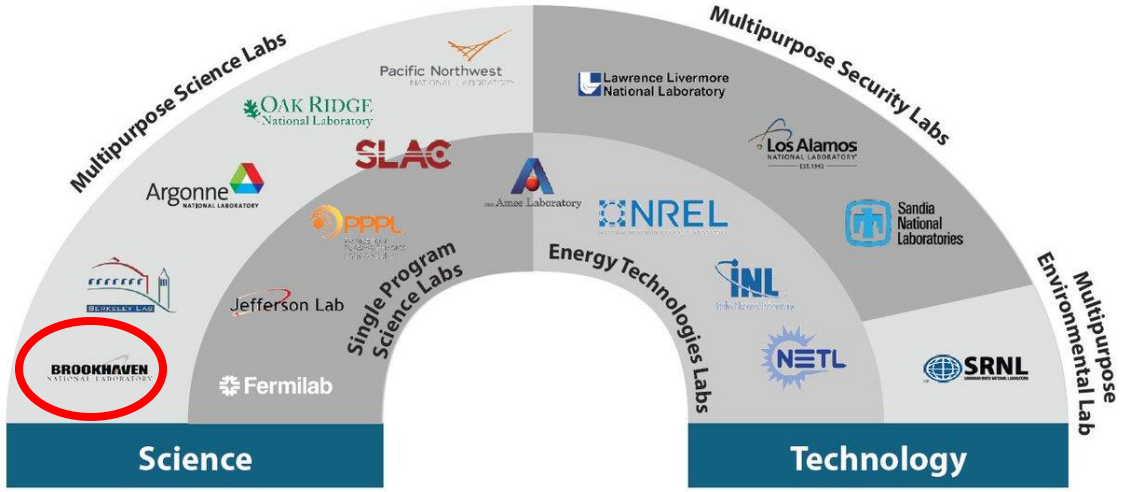
Nuclear Data & Applied Nuclear Science at the National Nuclear Data Center

Emanuel Chimanski (echimansk@bnl.gov)

TSU Initiative for Gravity and Experimental-nuclear Research
TIGER: April 9-11, 2025

@BrookhavenLab

not export controlled



Office of Science Laboratories

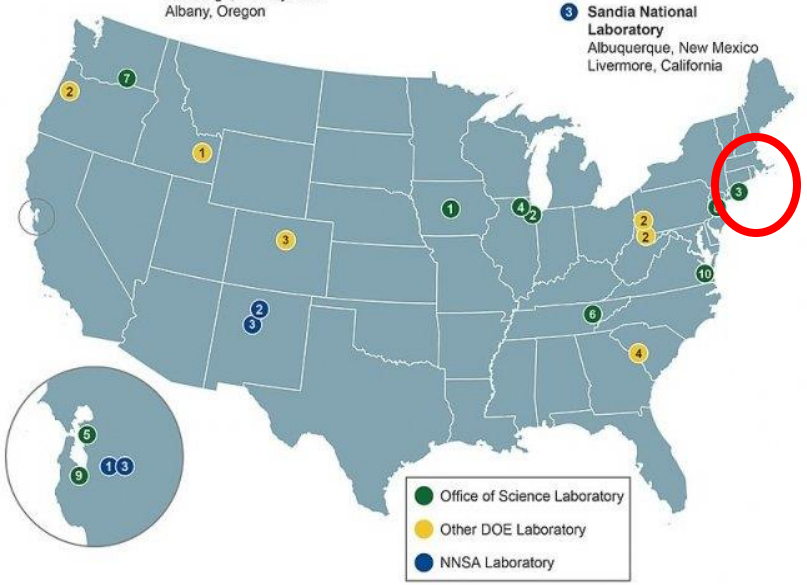
1. **Ames Laboratory**
   Ames, Iowa
2. **Argonne National Laboratory**
   Argonne, Illinois
3. **Brookhaven National Laboratory**
   Upton, New York
4. **Fermi National Accelerator Laboratory**
   Batavia, Illinois
5. **Lawrence Berkeley National Laboratory**
   Berkeley, California
6. **Oak Ridge National Laboratory**
   Oak Ridge, Tennessee
7. **Pacific Northwest National Laboratory**
   Richland, Washington
8. **Princeton Plasma Physics Laboratory**
   Princeton, New Jersey
9. **SLAC National Accelerator Laboratory**
   Menlo Park, California
10. **Thomas Jefferson National Accelerator Facility**
    Newport News, Virginia

Other DOE Laboratories

1. **Idaho National Laboratory**
   Idaho Falls, Idaho
2. **National Energy Technology Laboratory**
   Morgantown, West Virginia
   Pittsburgh, Pennsylvania
   Albany, Oregon
3. **National Renewable Energy Laboratory**
   Golden, Colorado
4. **Savannah River National Laboratory**
   Aiken, South Carolina

NNSA Laboratories

1. **Lawrence Livermore National Laboratory**
   Livermore, California
2. **Los Alamos National Laboratory**
   Los Alamos, New Mexico
3. **Sandia National Laboratory**
   Albuquerque, New Mexico
   Livermore, California



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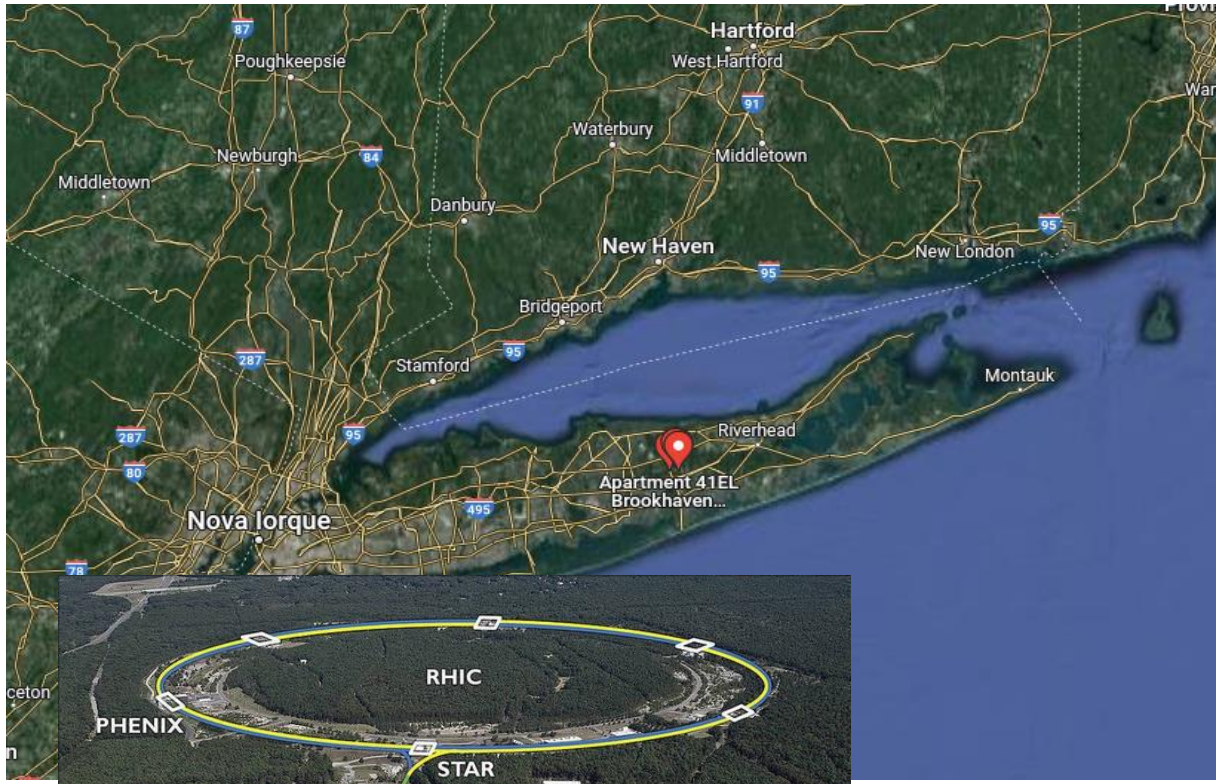
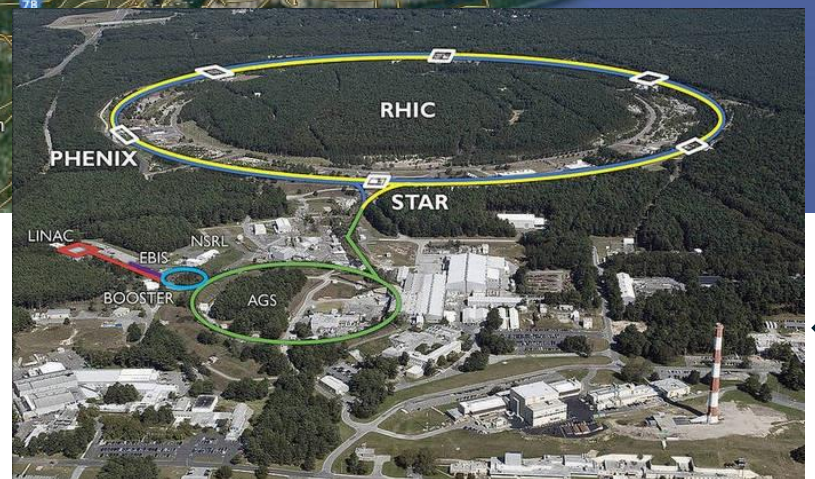
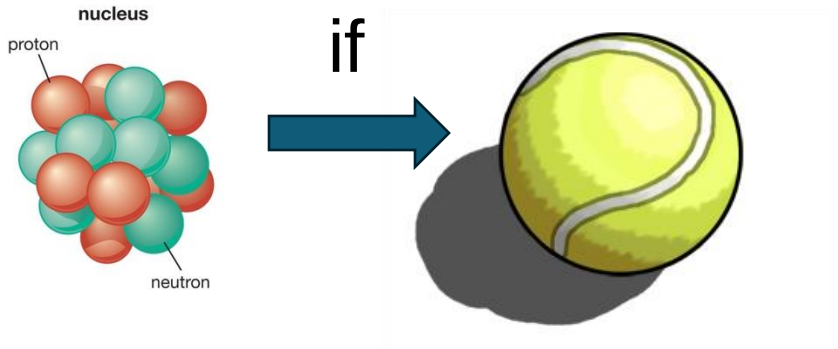


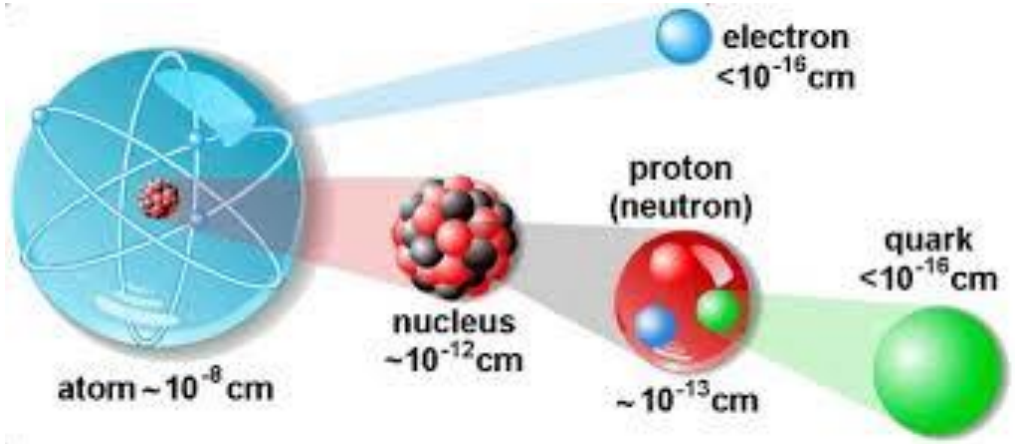


NNDC

Nuclear Scales

Microscopic objects ruled by Quantum Mechanics





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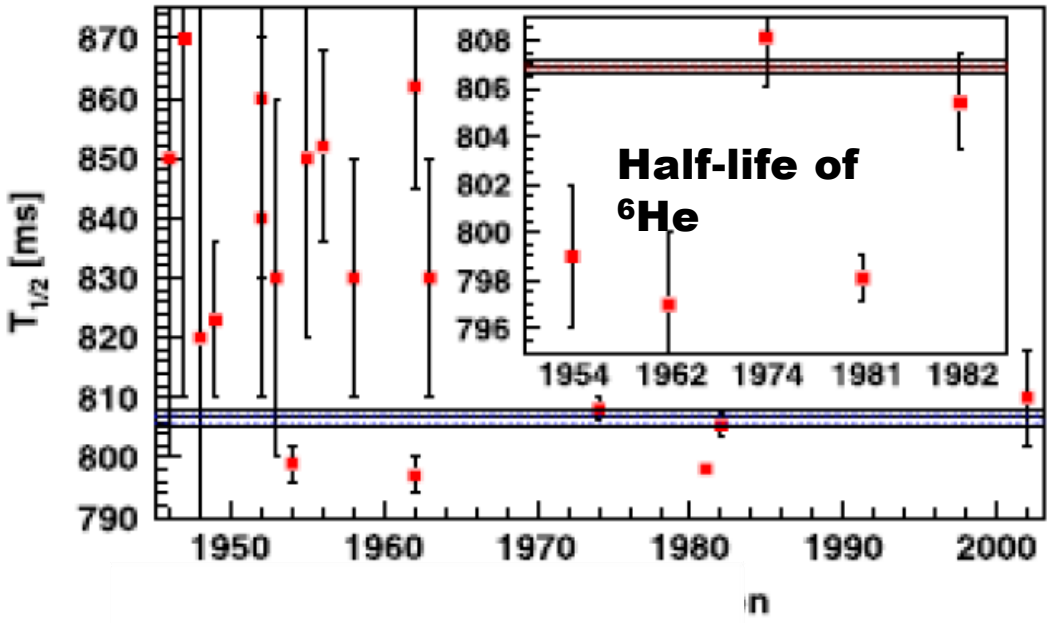
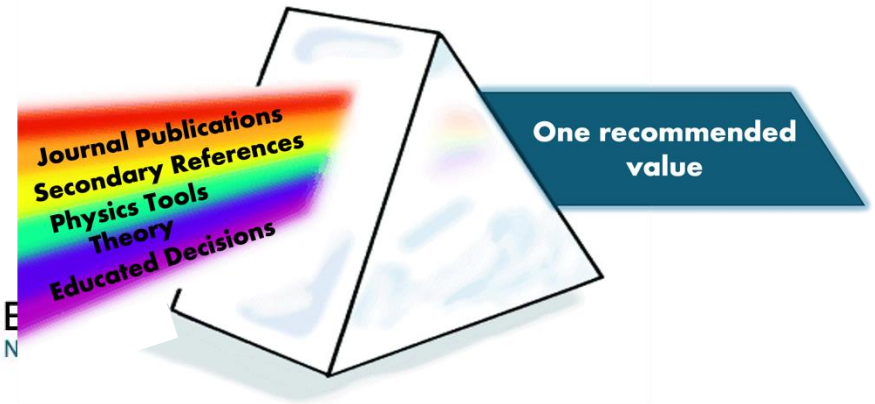
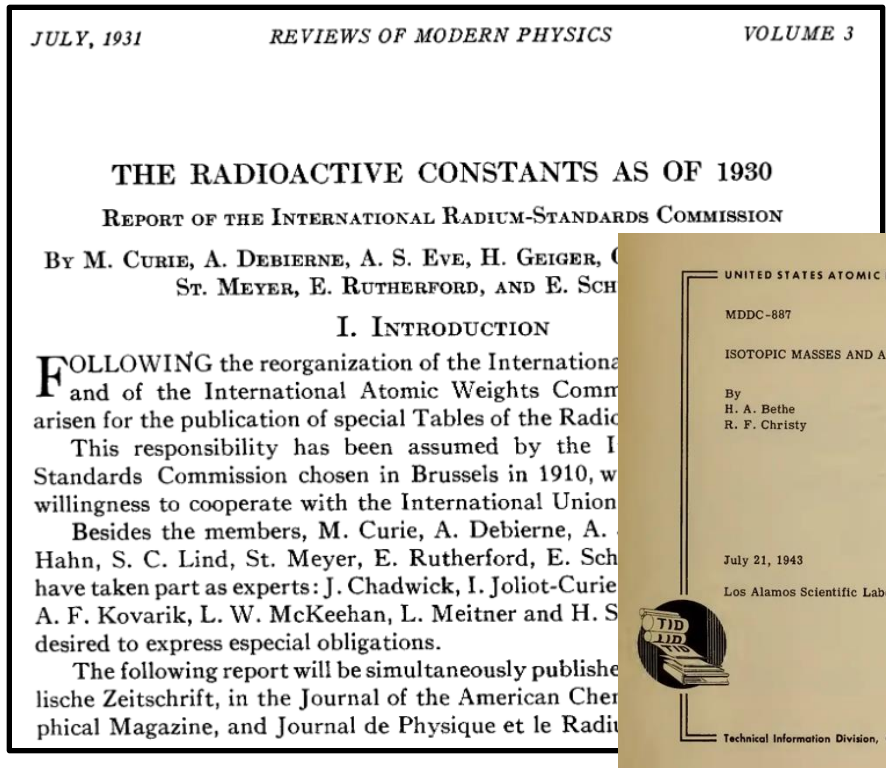
Evaluated Nuclear Data

Arbiters of the "Truth"





The need to count with a list of measured nuclear properties (**compilation**), that was critically reviewed (**evaluation**) and published for the use of other researchers (**dissemination**) has been present since the earliest times.



JULY, 1931 REVIEWS OF MODERN PHYSICS VOLUME 3

THE RADIOACTIVE CONSTANTS AS OF 1930

REPORT OF THE INTERNATIONAL RADIUM-STANDARDS COMMISSION

BY M. CURIE, A. DEBIERNE, A. S. EVE, H. GEIGER, ... ST. MEYER, E. RUTHERFORD, AND E. SCH...

I. INTRODUCTION

FOLLOWING the reorganization of the Internationa... and of the International Atomic Weights Comm... arisen for the publication of special Tables of the Radio...

This responsibility has been assumed by the I... Standards Commission chosen in Brussels in 1910, w... willingness to cooperate with the International Union...

Besides the members, M. Curie, A. Debierne, A. ... Hahn, S. C. Lind, St. Meyer, E. Rutherford, E. Sch... have taken part as experts: J. Chadwick, I. Joliot-Curie... A. F. Kovarik, L. W. McKeehan, L. Meitner and H. S... desired to express especial obligations.

The following report will be simultaneously publishe... lische Zeitschrift, in the Journal of the American Che... phical Magazine, and Journal de Physique et le Radi...

UNITED STATES ATOMIC ENERGY COMMISSION

MDDC-887

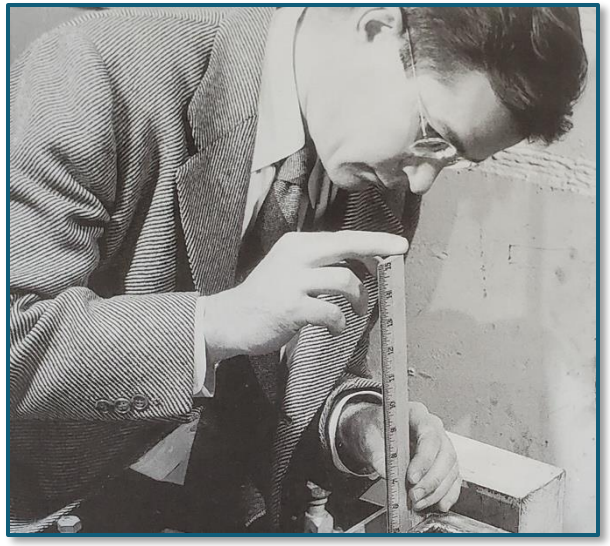
ISOTOPIC MASSES AND ABUNDANCES (LADC-285)

By
H. A. Bethe
R. F. Christy

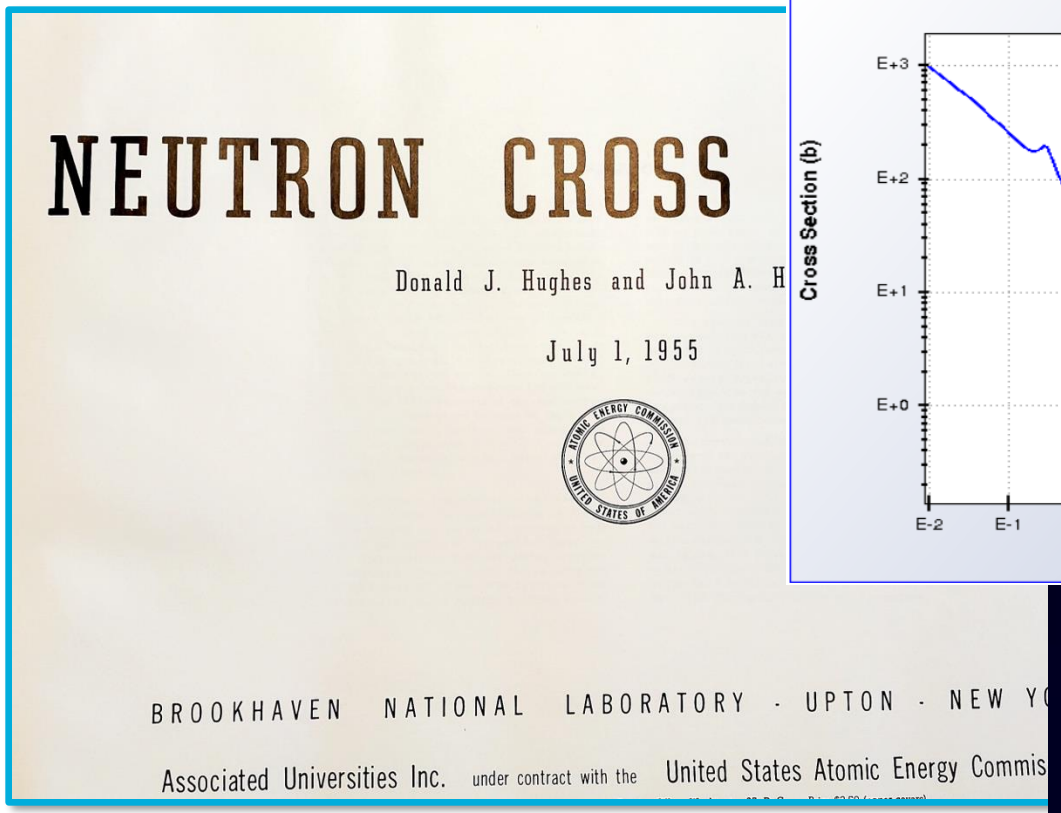
July 21, 1943

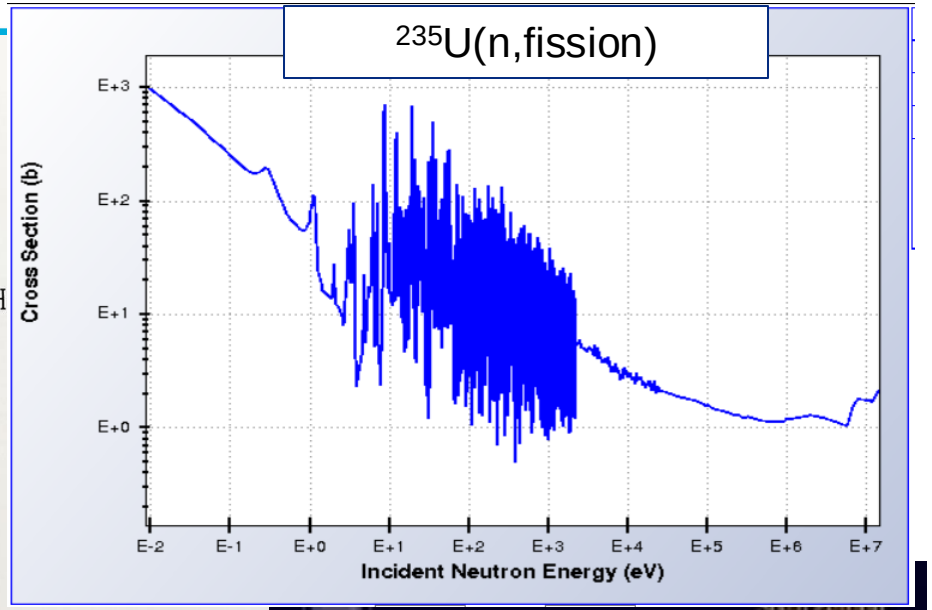
Los Alamos Scientific Laboratory

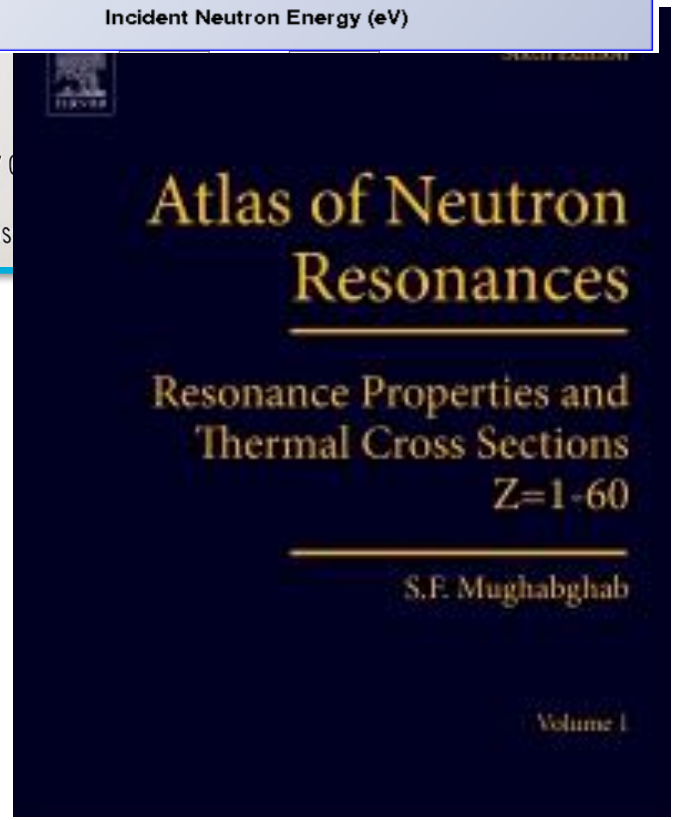
Technical Information Division, ORE, Oak Ridge, Tennessee



Donald Hughes (1915-1960)



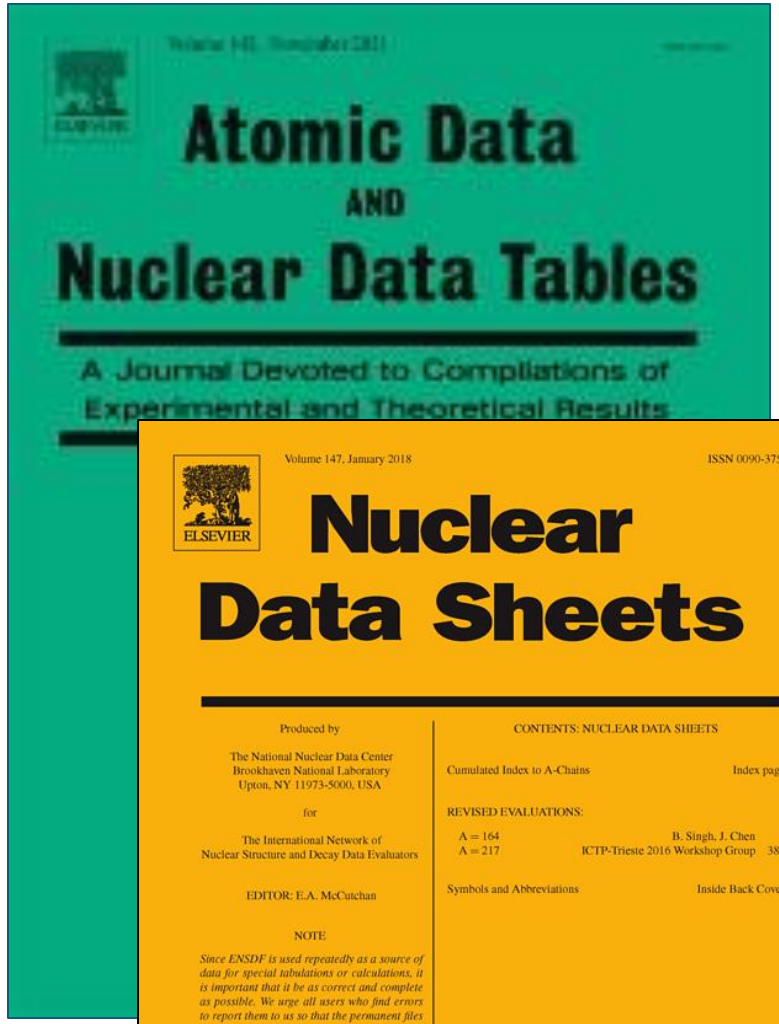




- PhD from the University of Chicago, working with Arthur Compton on cosmic rays, 1940.
- Joined Manhattan Project in 1942.
- Worked at Hanford site in 1944, now PNNL.
- Director of ANL's Nuclear Physics Division, 1945-1949.
- Senior Physicist at BNL, 1949-1960. *Dean of BNL's neutron physicists, the single most influential experimenter at the reactor and leader of its largest group (from Robert Crease's book on BNL history).*
- Started compilation and evaluation of neutron cross section data.
- Work has continued with the 2018 publication of Atlas of Neutron Resonances.

Katherine Way (1902 – 1995)

- PhD from Columbia University, working with John Wheeler on nuclear reactions,1938.
- Joined Manhattan Project in 1943.
- Worked in ORNL, 1945-1949, and NIST from 1949.
- Founder of the Nuclear Data Project.
- Founder and editor of the Nuclear Data Sheets and Atomic Data and Nuclear Data Tables journals in the 1960s.
- Current editors are Elizabeth McCutchan (NDS) and Boris Pritychenko (ADNDT).



Since the mid-1970s, an important fraction of the NNDC activities have developed from the foundational works of Donald Hughes and Katherine way

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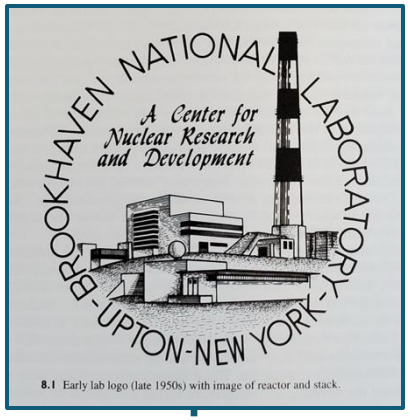
The beginning



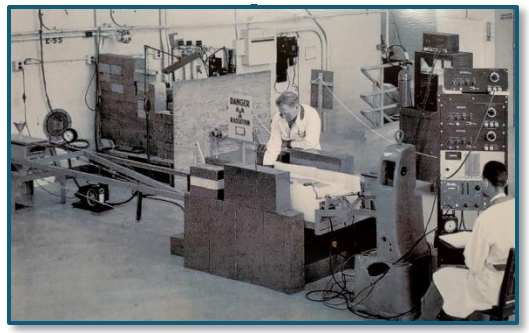
8.1 Early lab logo (late 1950s) with image of reactor and stack.

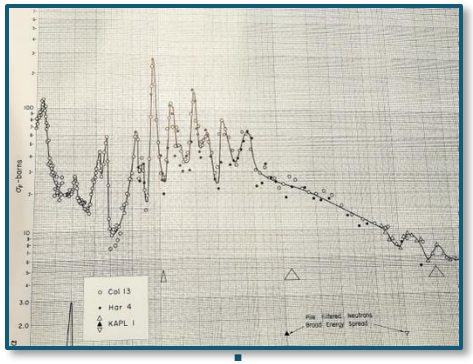
1947

BNL is founded

1952

Nuclear Data efforts start in BNL





1961

Nuclear Data group becomes the Sigma Center

Cross Section Evaluation Working Group

1966

BNL bulletin, February 20, 1969.

Project: 05055
NNCSC-Data Compilation

1967

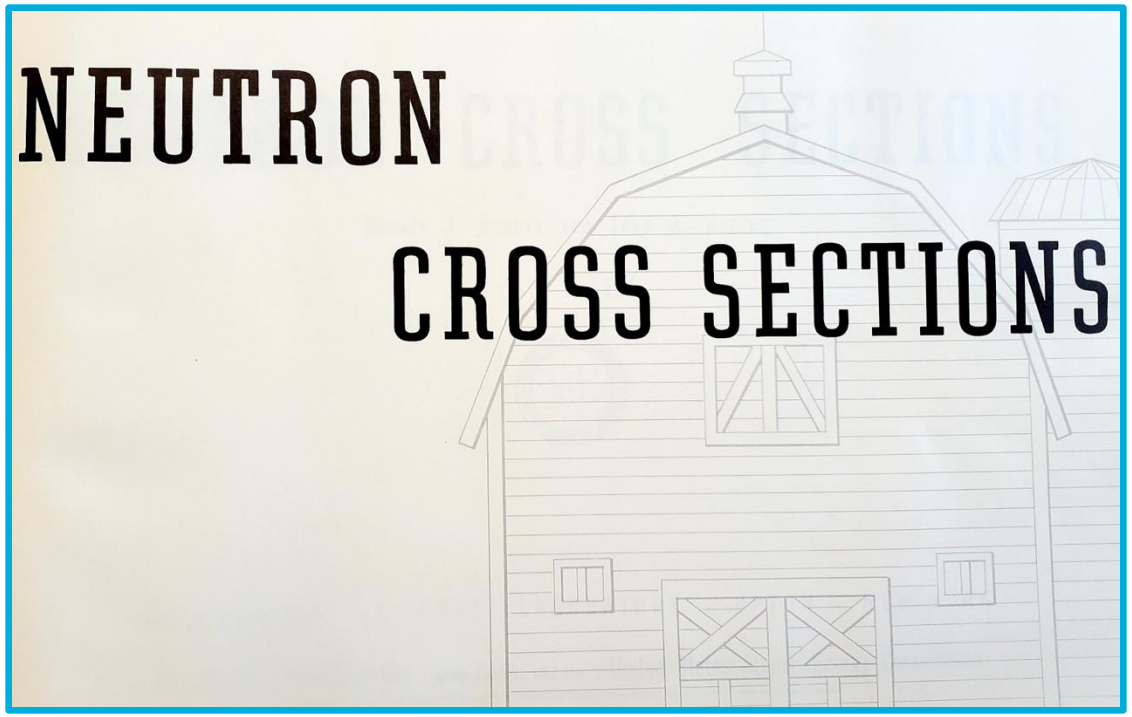
National Neutron Cross Section Center

Brookhaven National Laboratory

Branding 101!

- The Greek letter sigma, **σ**, is used as a symbol for nuclear cross sections, which measure the probability that a neutron interacts with a given nucleus.
- The group founded by Donald Hughes was known as the **Sigma Center**!
- The '**barn**' unit, **1 barn=10^{-24} cm^2**, is used for nuclear cross sections.
- The **barn** has been used as a symbol of the group from the very beginning!

Element	Isotope (%, $T_{1/2}$)	Reaction Cross Sections (2200 m/s) σ_{abs}		σ_{act}
$_1H$		330 ± 3 mb		
	H^1(~100)			
	H^2(0.015)	0.46 ± 0.10 mb	12.4y	0.57 ± 0.01 mb



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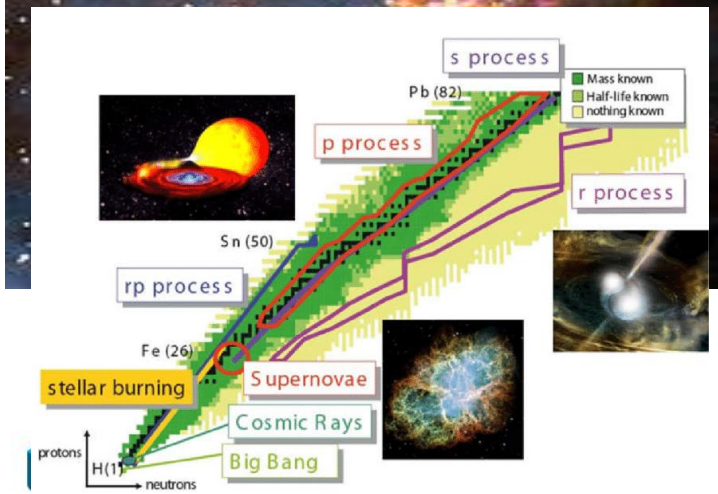
NNDC

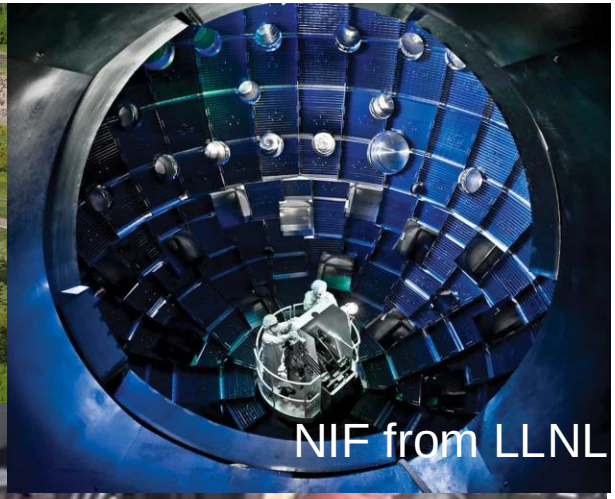
Modern nuclear applications require detailed and complex modeling

Nucleosynthesis

- **Capture reactions** (required)
- **Stellar evolution**;
- Heavy-element **nucleosynthesis**;

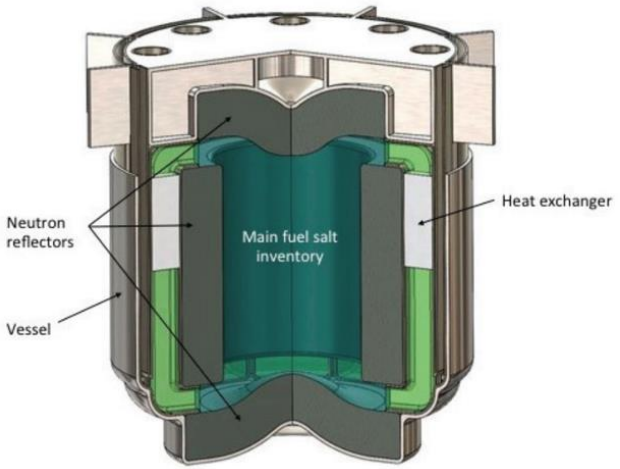


Peter, Particles 2020, 3(2), 320-335



NIF from LLNL

ITER



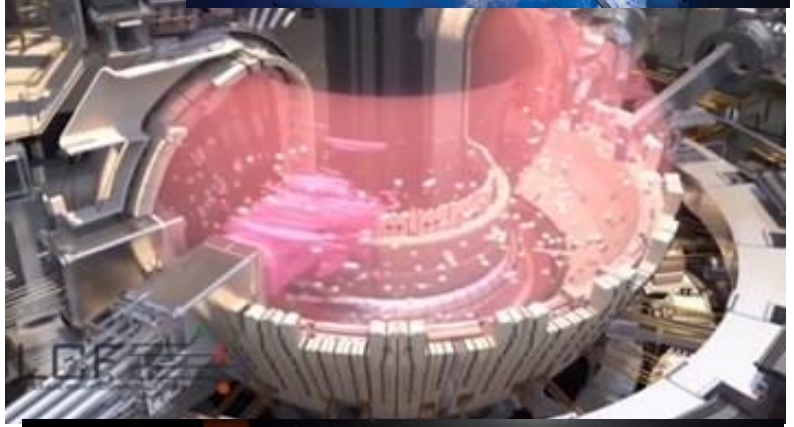
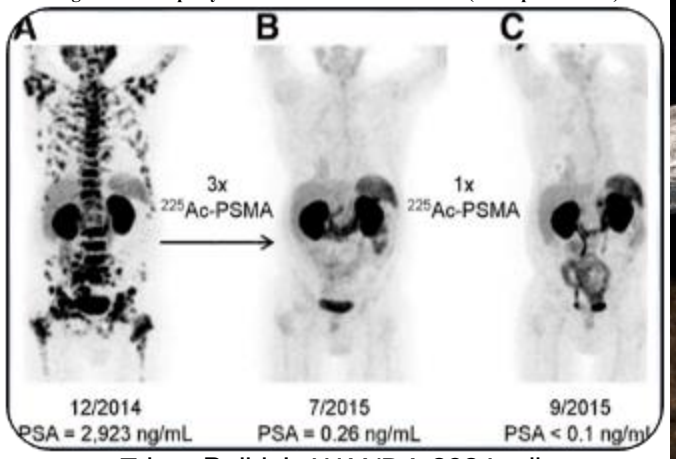
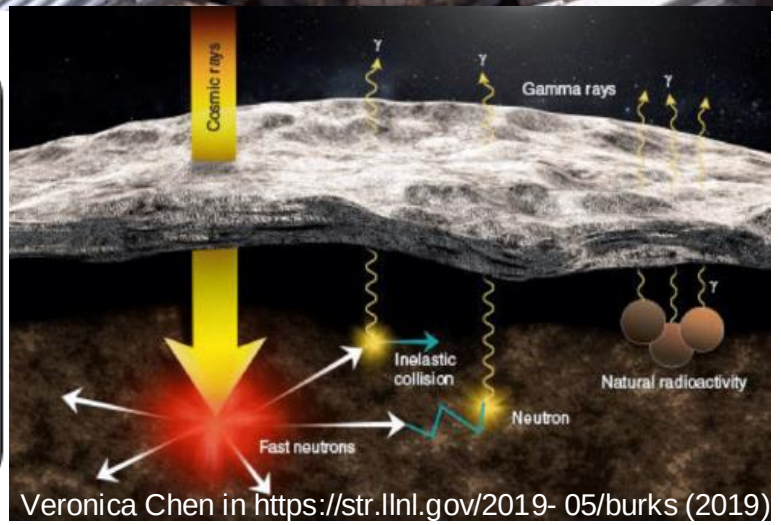


Figure 8. Exemplary molten salt fast reactor model (Terrapower 2020).

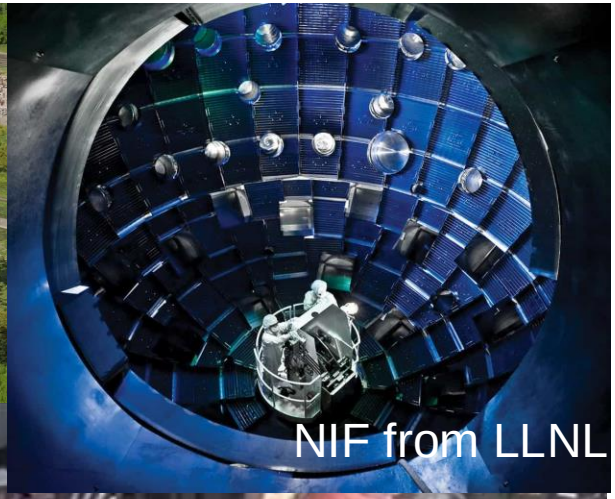


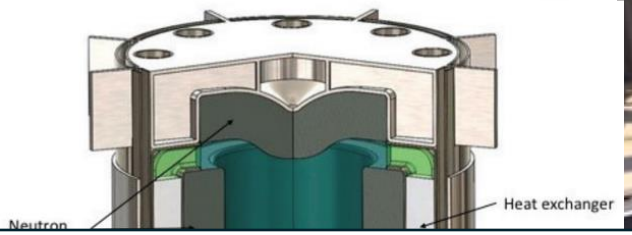
Ethan Balkin's WANDA 2024 talk



Veronica Chen in https://str.llnl.gov/2019- 05/burks (2019)

Modern nuclear applications require detailed and complex modeling





MCNP6

PHITS
Particle and Heavy Ion Transport code System

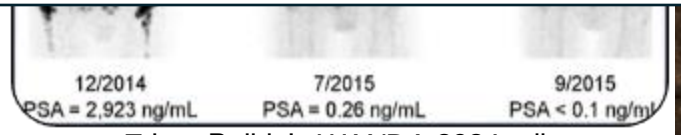
GEANT4
A SIMULATION TOOLKIT

scale
Nuclear Systems Modeling & Simulation

2000
GENIE
Applications
Software

OpenMC

FLUKA



Ethan Balkin's WANDA 2024 talk

Veronica Chen in https://str.llnl.gov/2019- 05/burks (2019)

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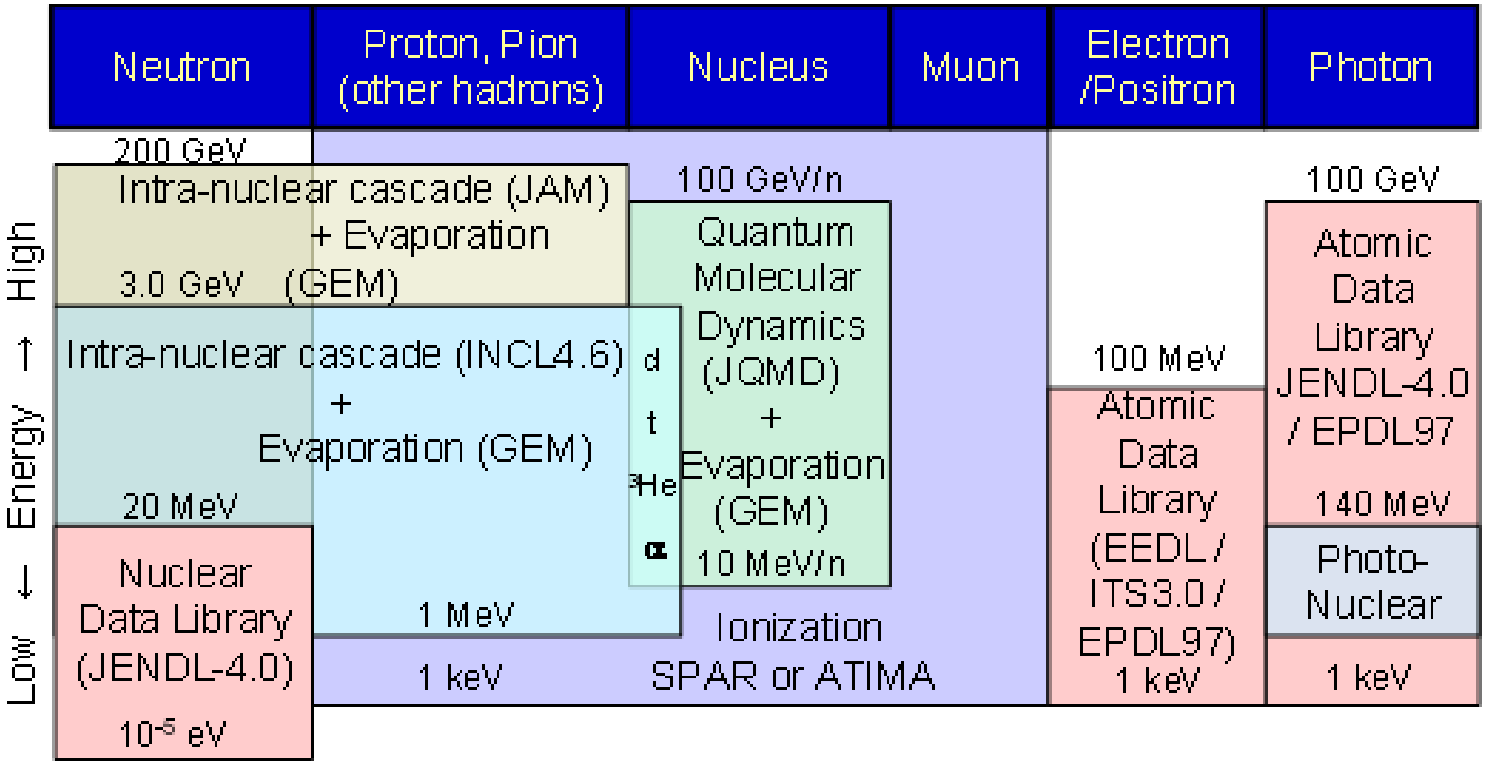
Nuclear data's often forgotten role

Because nuclear data lives "under the hood" in many applications, it is not obvious to user

When there's trouble, these are the options:

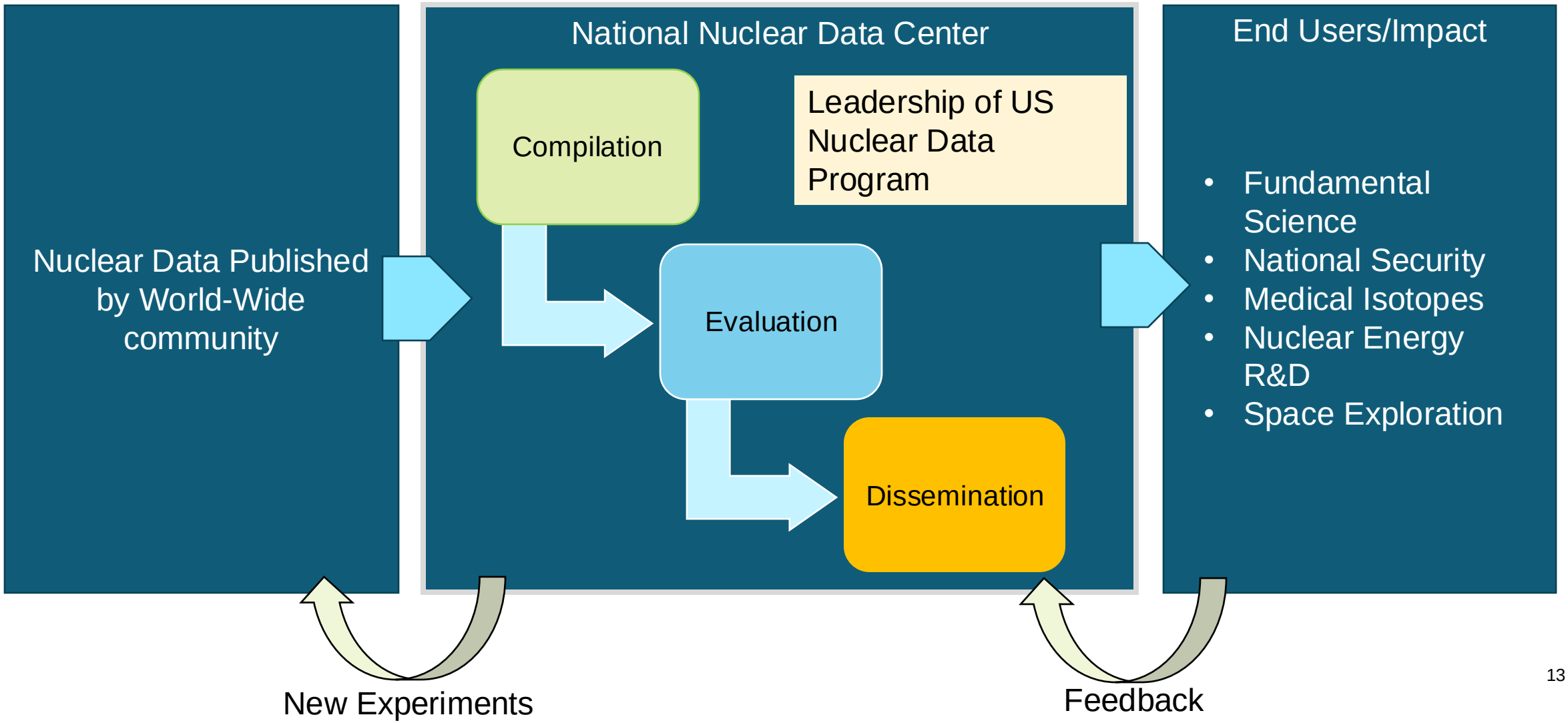
- Ignore the issues
- Engineer away trouble (potentially missing opportunities)
- Dig under the hood and engage with us



Model matrix of PHITS transport code (https://phits.jaea.go.jp/OvMapOfModels.html)

Red boxes = ENDF nuclear data

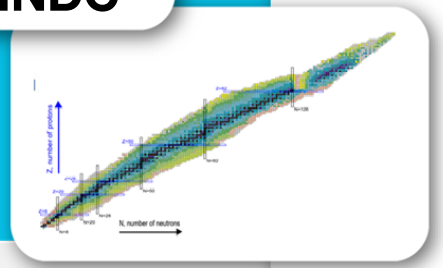
NNDC's pivotal role

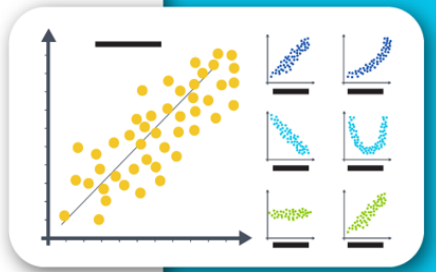


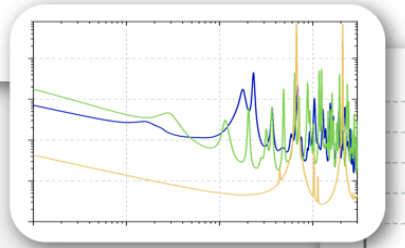
NATIONAL NUCLEAR DATA CENTER

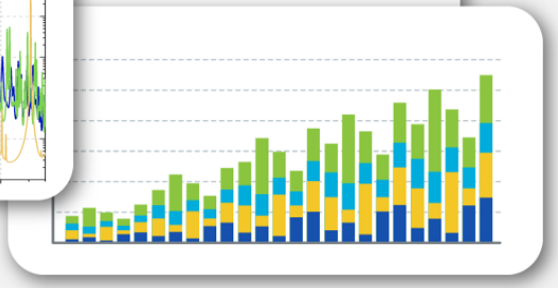
NNDC

Current, accurate, authoritative data in areas of nuclear science and engineering









PuRe Data Resources

Office of Science designated PuRe Data Resource | open data | data repositories, knowledgebases, analysis platforms

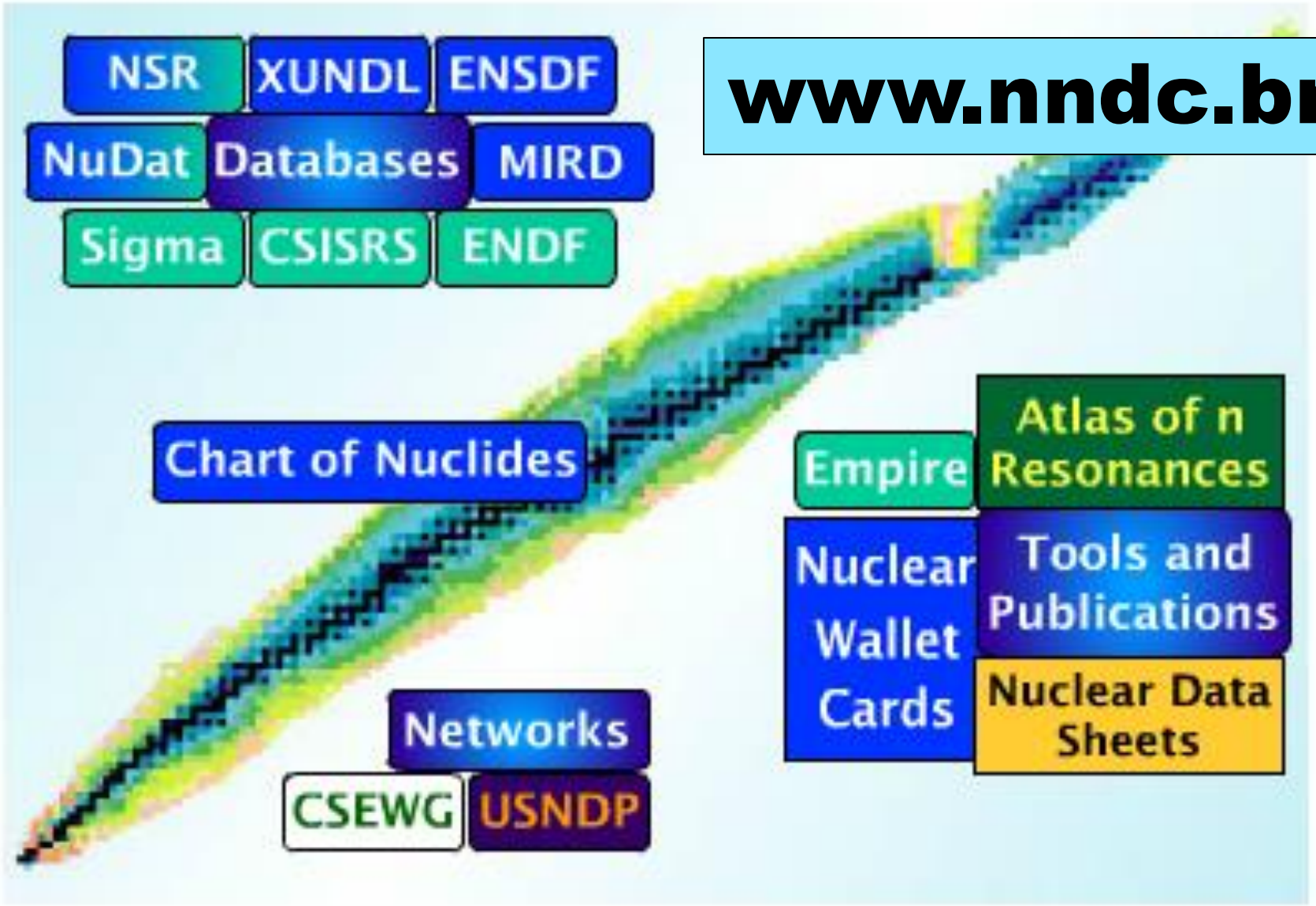
NNDC Vision & Mission

Be the premier global resource for nuclear data and plan to:

- ❑ Implement AI/ML algorithms to reduce the time from data publication to integration in a recommended library to less than two years.
- ❑ Establish an open data repository for low-energy nuclear physics.
- ❑ Advance dissemination efforts with modern and efficient software tools.
- ❑ Sustain a robust nuclear physics research portfolio, including the development of an experimental program to accelerate isotope production science.

The NNDC is the lead and largest unit of the U.S. Nuclear Data Program (USNDP), whose mission is to provide current, accurate, authoritative data for workers in pure and applied areas of nuclear science and engineering.

National Nuclear Data Center

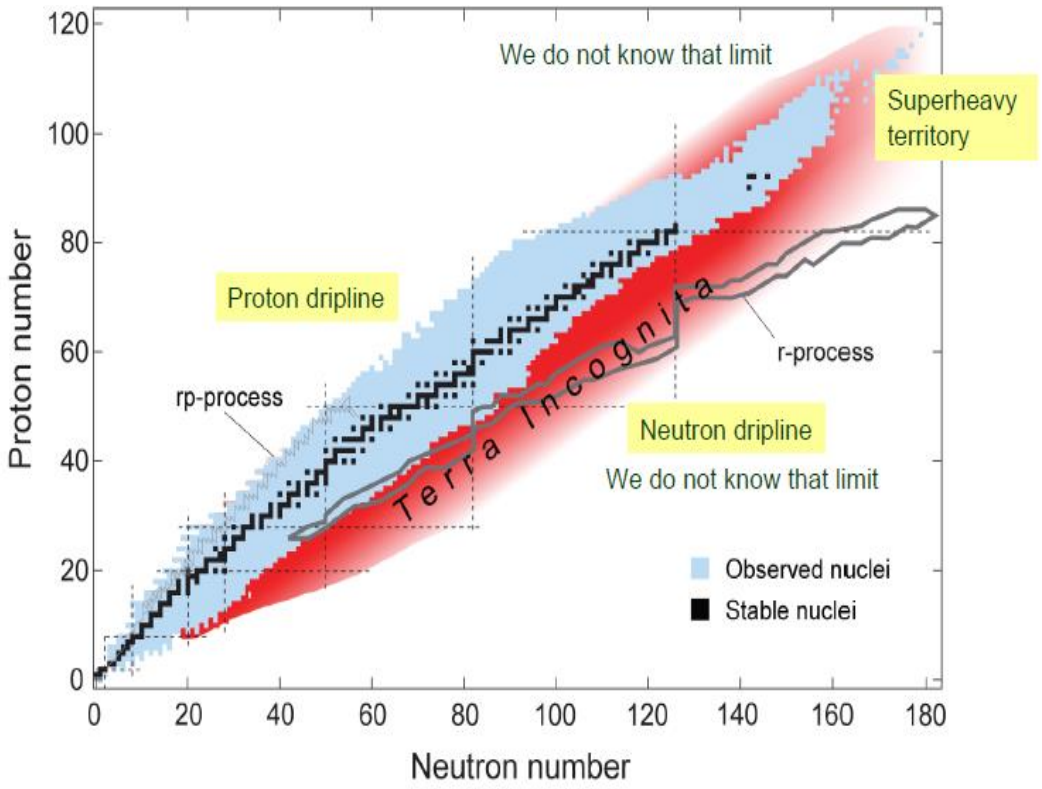


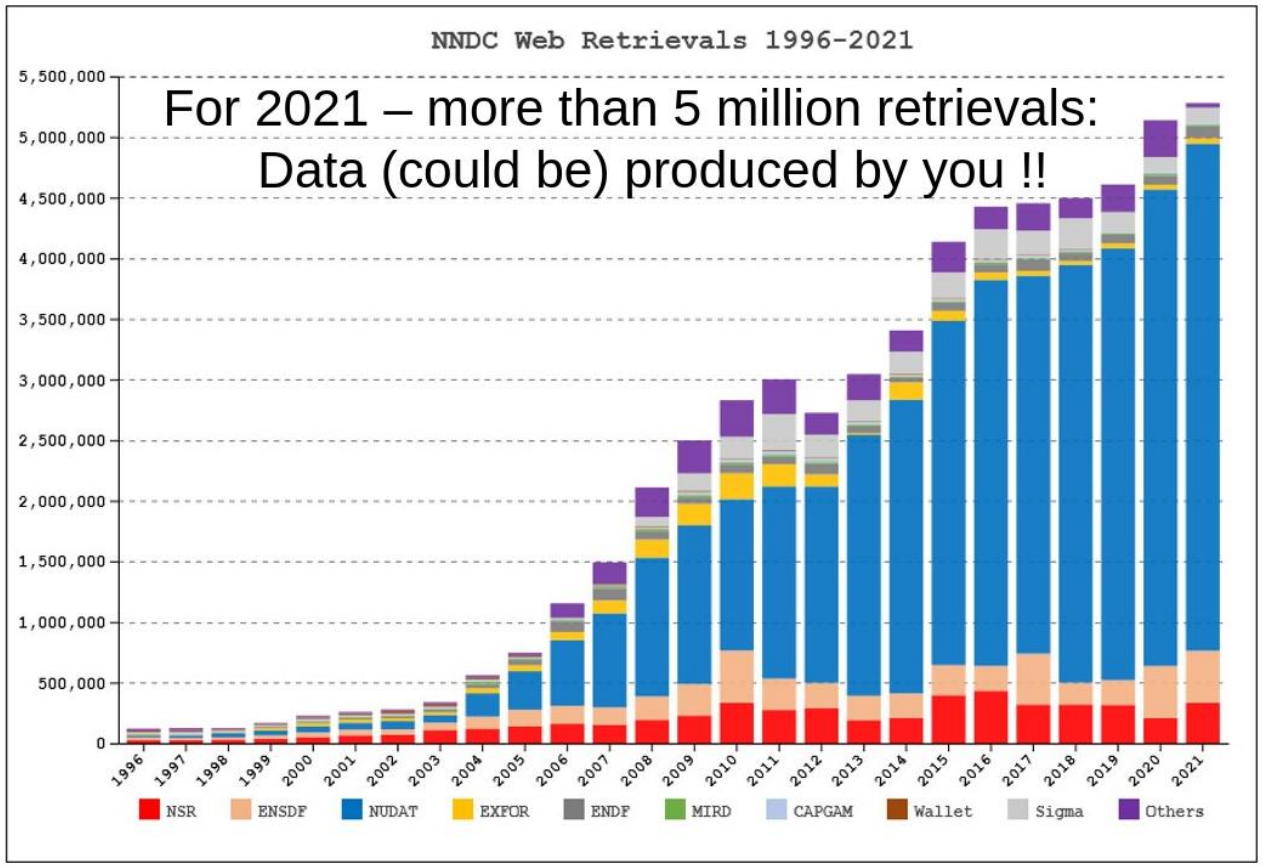
www.nndc.bnl.gov

Users of Evaluated Libraries

More than 3,400 have been produced

6000-8000 are predicted





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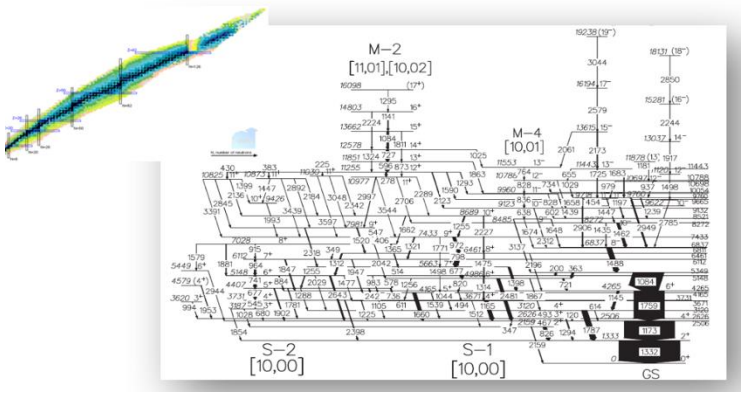
Evaluated Nuclear Data

ENSDF
Evaluated Nuclear Structure Data File

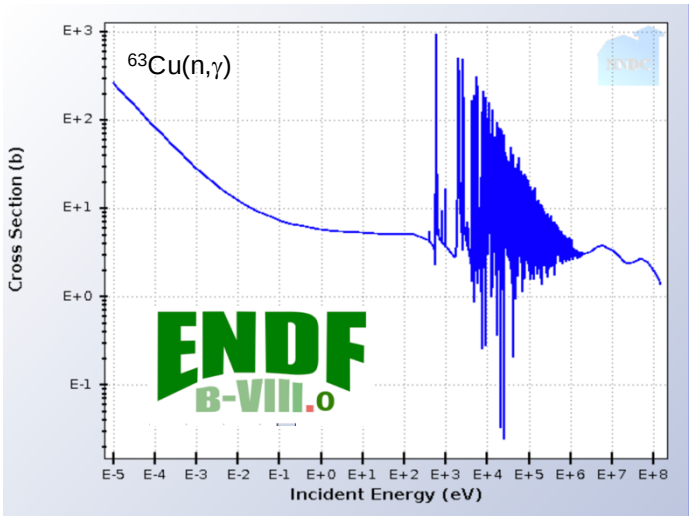


Measured data

- Structure and Decay Properties

If it was measured it is here

+



ENDF
Evaluated Nuclear Data File

Experimental supplemented with theoretical data

- Cross sections
- Particle spectra
- and much more…

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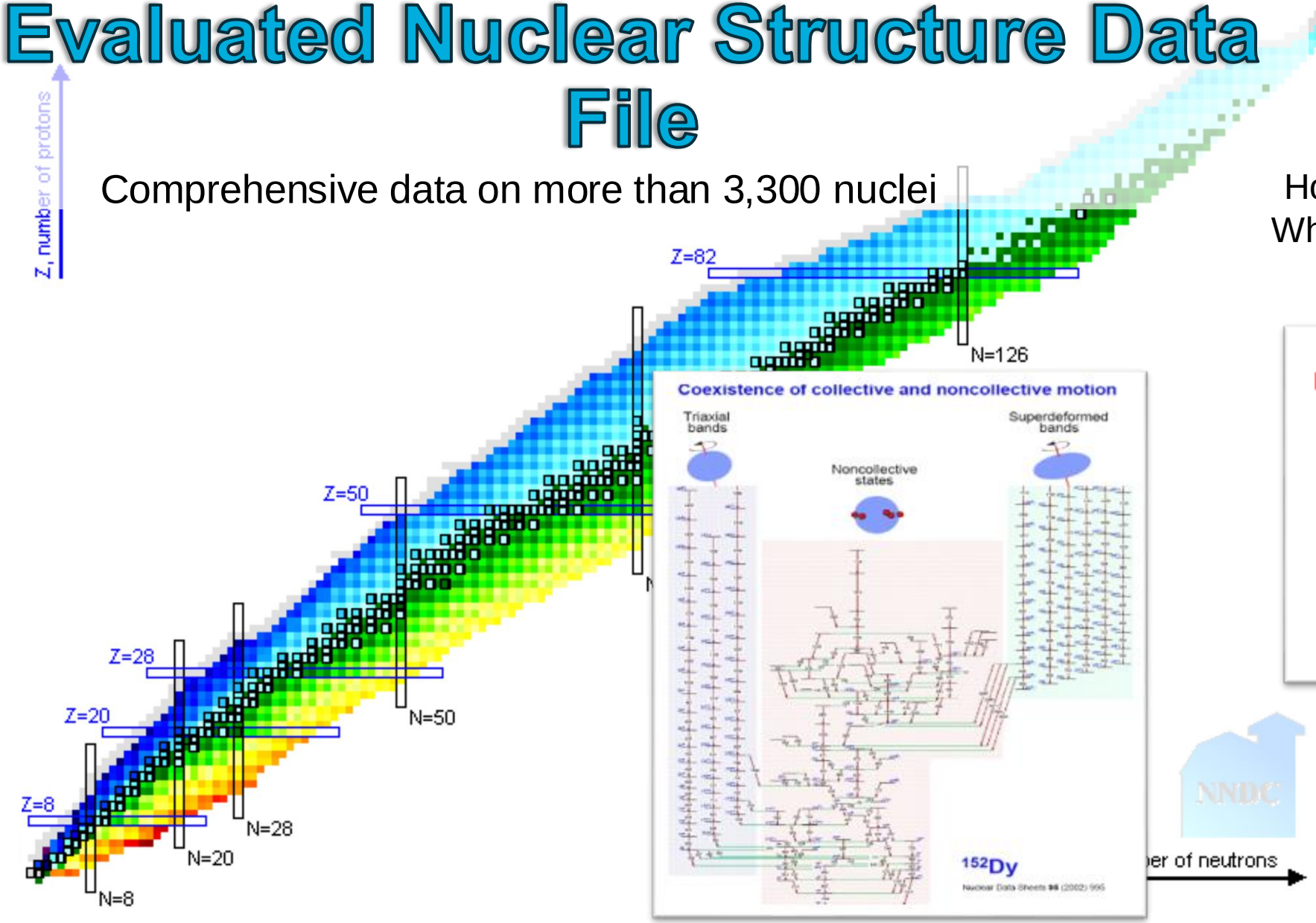
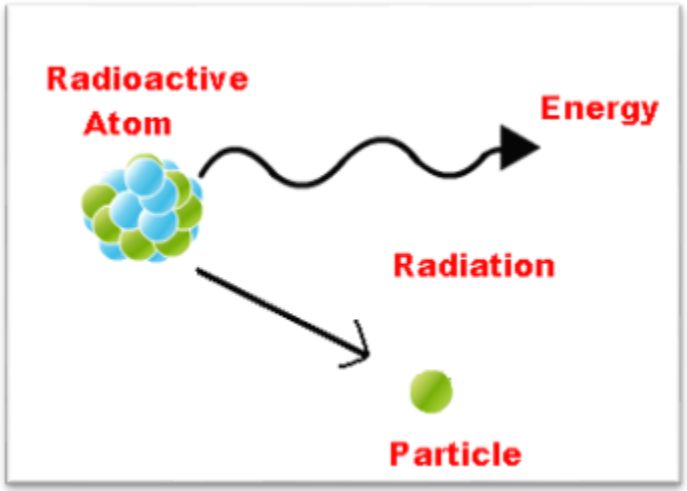
ENSDF

Evaluated Nuclear Structure Data File

Comprehensive data on more than 3,300 nuclei



How long does nucleus live for? What are energies and amount of radiation produced?



ENSDF : the ONLY comprehensive resource for

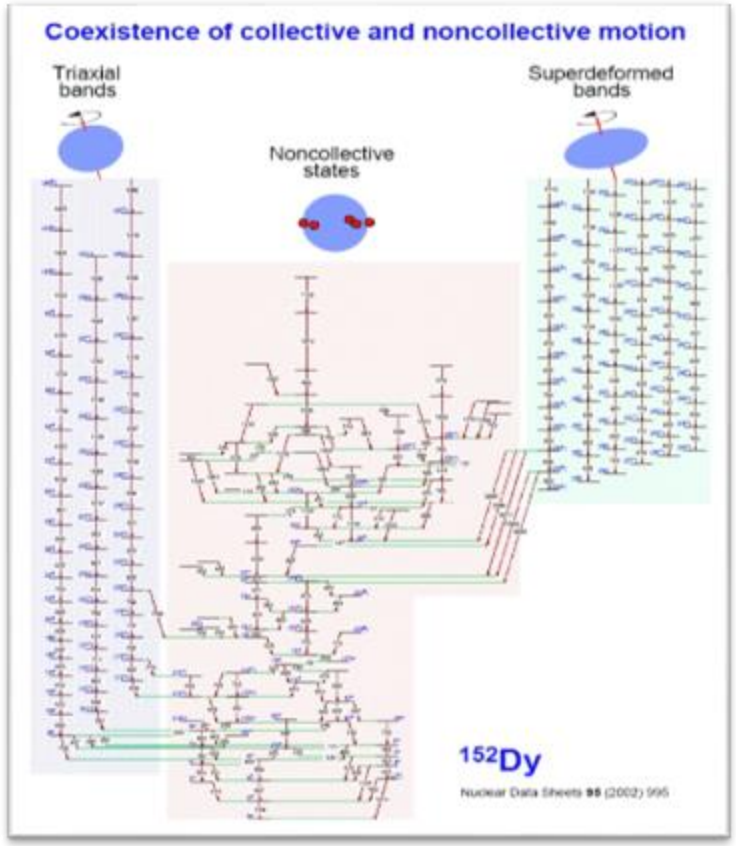
Nuclear Structure

Discrete Quantized States

- Excitation Energy
- Half-life
- Angular Momentum
- Magnetic Moment
- Configuration
- …

Emitted Radiation

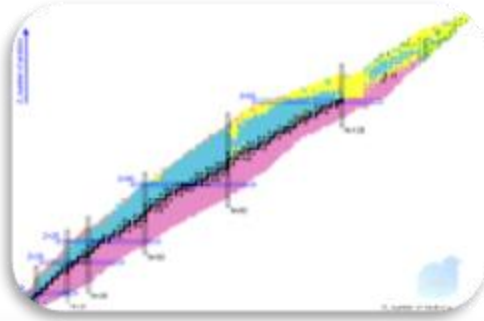
- Energy
- Intensity
- Dipole, Quadrupole, …
- Mixing ratio
- Conversion coefficient

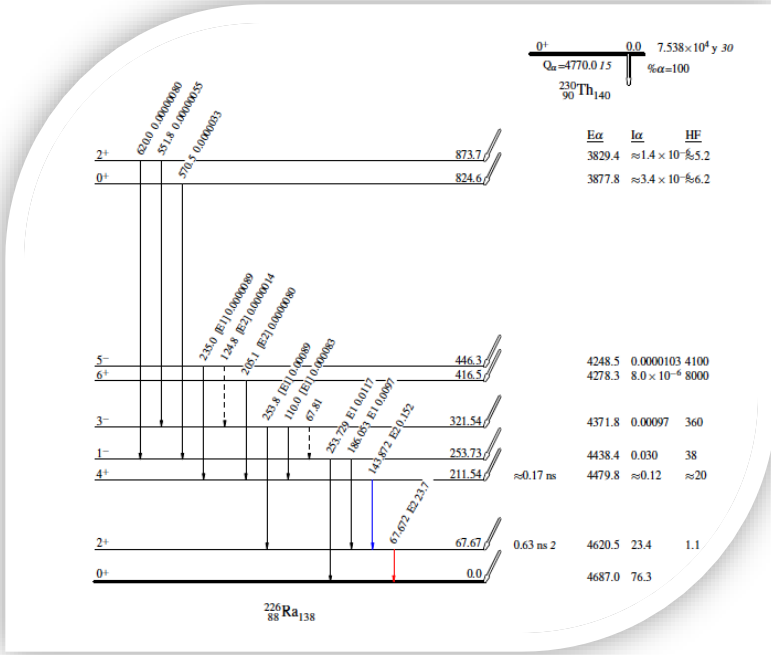


Nuclear Decay Data

For each decay type:

- Half-life
- Branching ratio
- Energy
- Intensity
- Coincidences
- …





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The Cross Section Evaluation Working Group produces ENDF/B library

- **Formed 1966 & Chaired by BNL**
- **Currently ~200 members of the collaboration from 25 institutions**
  - US programs, industry and international partners
  - If you see something in the library, at some point a sponsor somewhere wanted it
- **All steps of nuclear data pipeline coordinated through CSEWG**
- **Depending on what needs done, getting required data in library can be major effort**

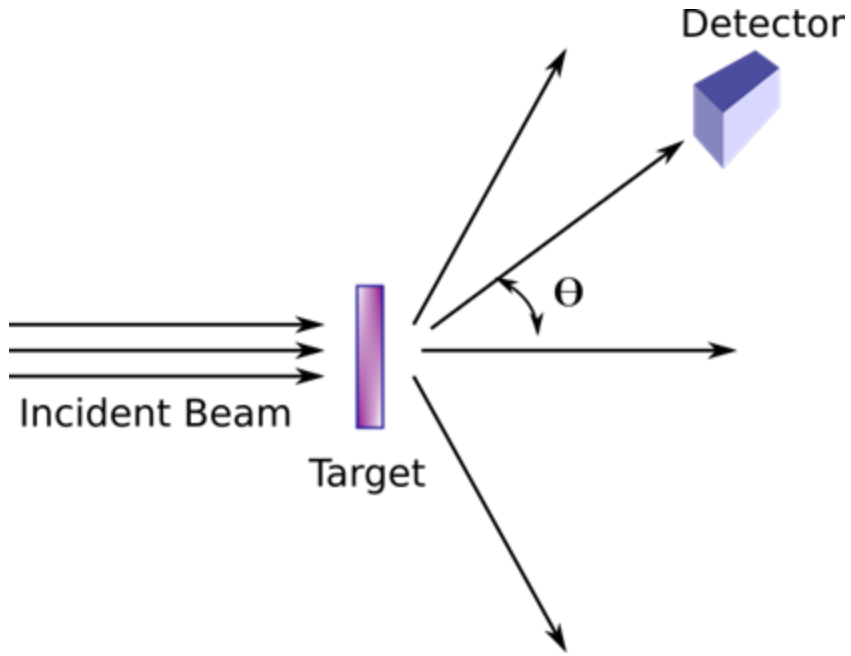
CSEWG collaboration meeting, November 2023

Always open to new users and collaborators

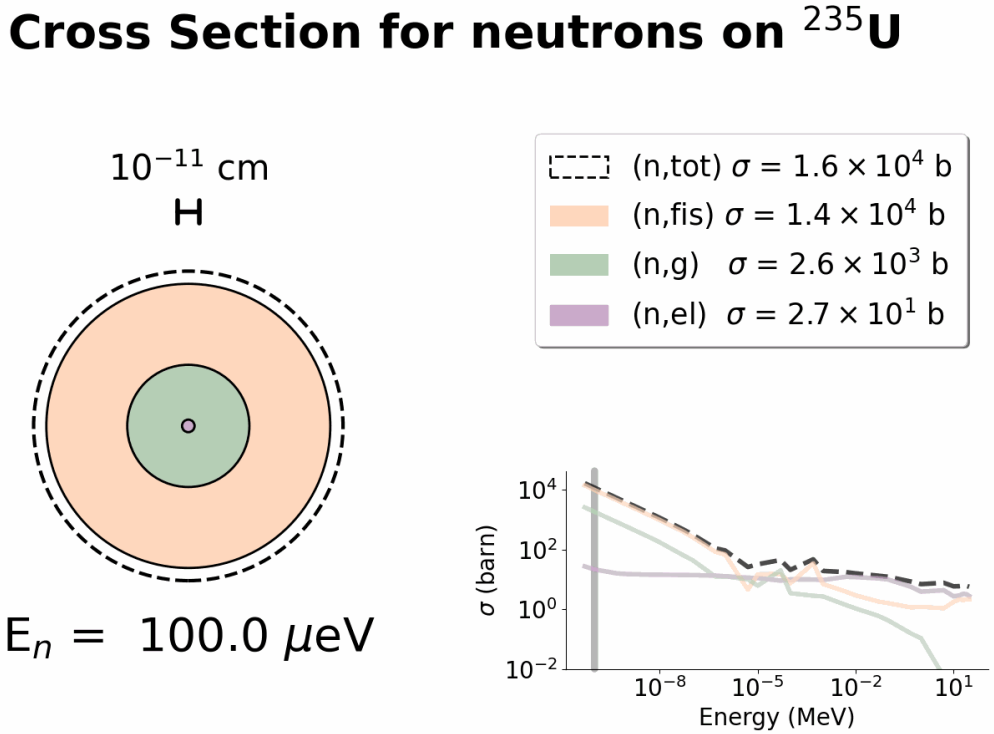
National Laboratory

The General Picture

- **Cross section σ** is a measure of the chance (probability) that a nuclear interaction between particles occur.



In analogy to an interaction zone, it is measured in **units of area**: square meters or square feet or barns (1 **barn** = 10^{-28} m^2).



Brookhaven National Laboratory

General Picture of Nuclear Reactions: Mechanisms

Compound nucleus:

a + A → C* → b + B

Hauser-Feshbach model

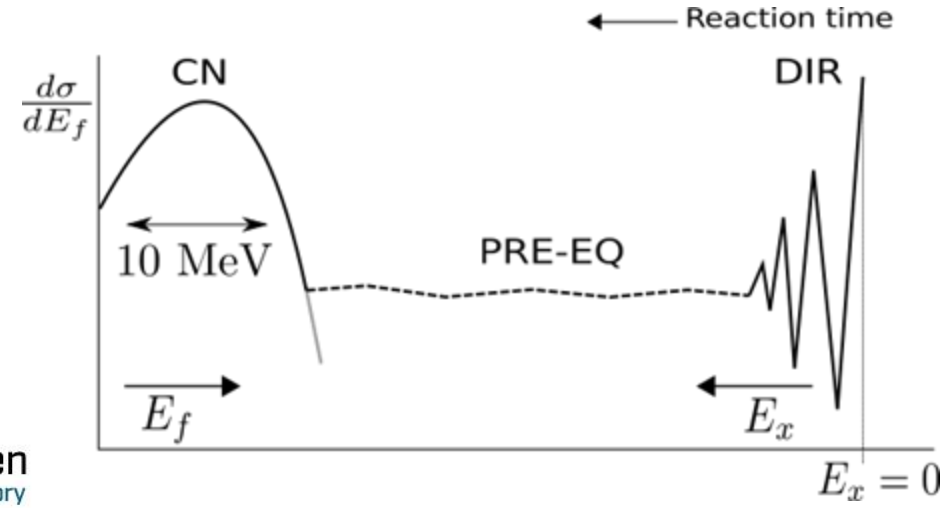
Pre-equilibrium:

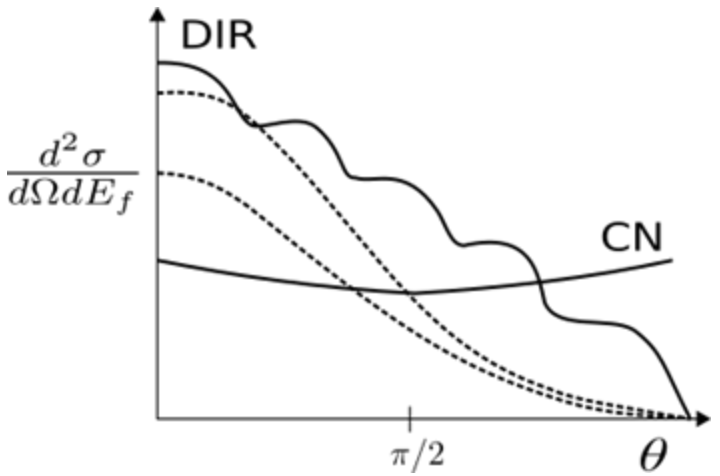
Exciton and
Multi-Step theory

Direct reactions:

a + A → b + B

Single p-t interaction





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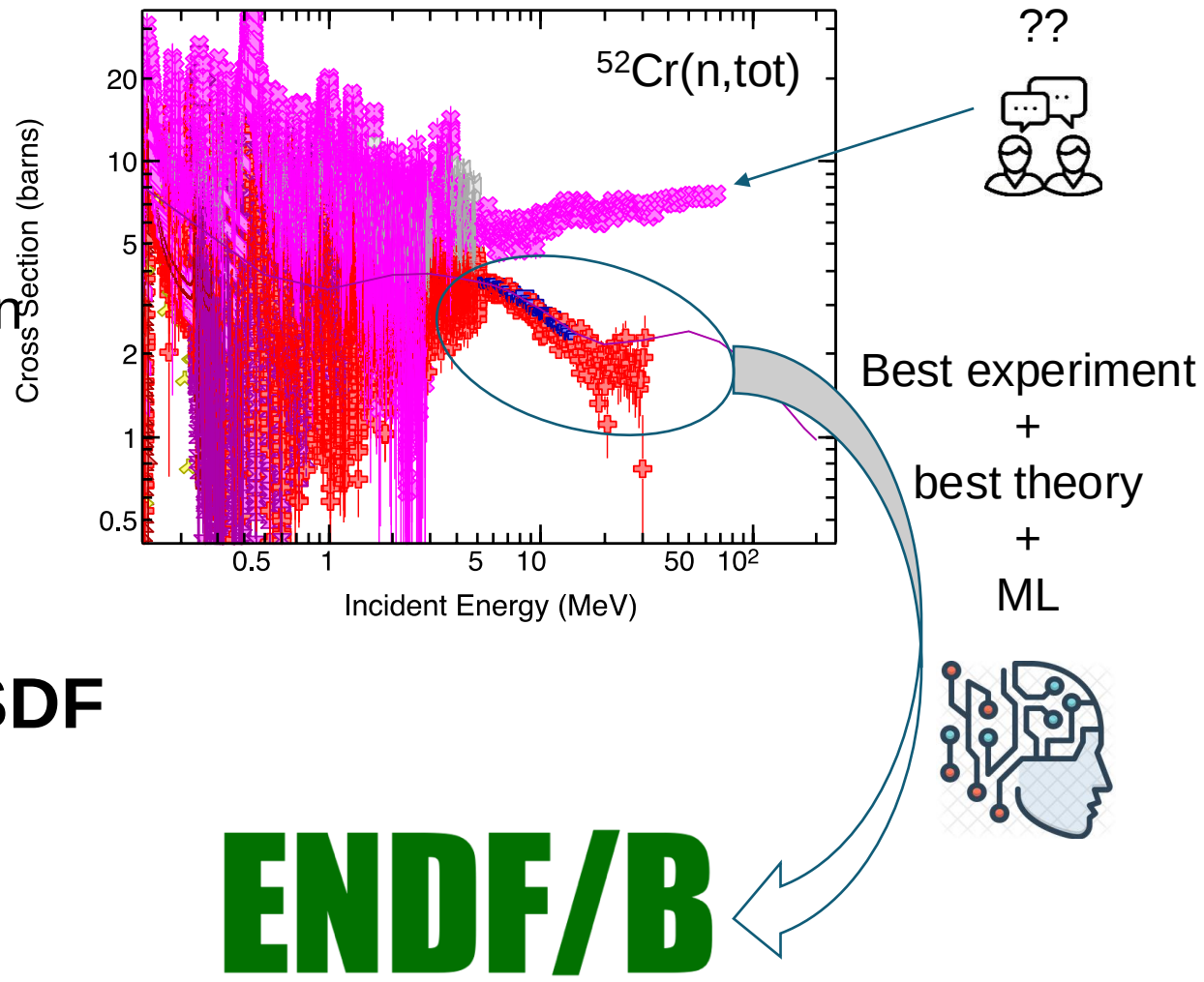
The ENDF library provides everything one needs to model a neutron's interaction with materials

- **For each target material**:
  - Total cross section
  - For every energetically allow reaction
    - Cross section
    - For each emitted particle
      - Outgoing multiplicity and
      - energy angle distribution
- **Decay data distilled from ENSDF**
- **Fission product yield data**
- **Uncertainty/covariance data**



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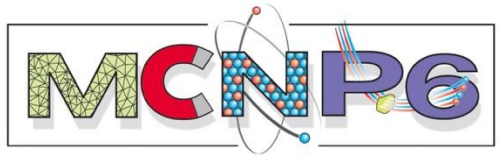
Many nuclear modeling packages embed ENDF/B data

- Reactor design, simulation and licensing codes.
- Nuclear waste and repositories.
- Radiation spectroscopy, dose, detectors and shielding.
- Defense
- CTBTO
- Non-proliferation
- Space physics
- Industry
- …

ENDF/B



ENDF/B-VIII.0 was released on 2 Feb. 2018

Library detailed in Nuclear Data Sheets vol. 148 (2018)

Happy 50th Anniversary! *

* ENDF/B-I was released in June 1968

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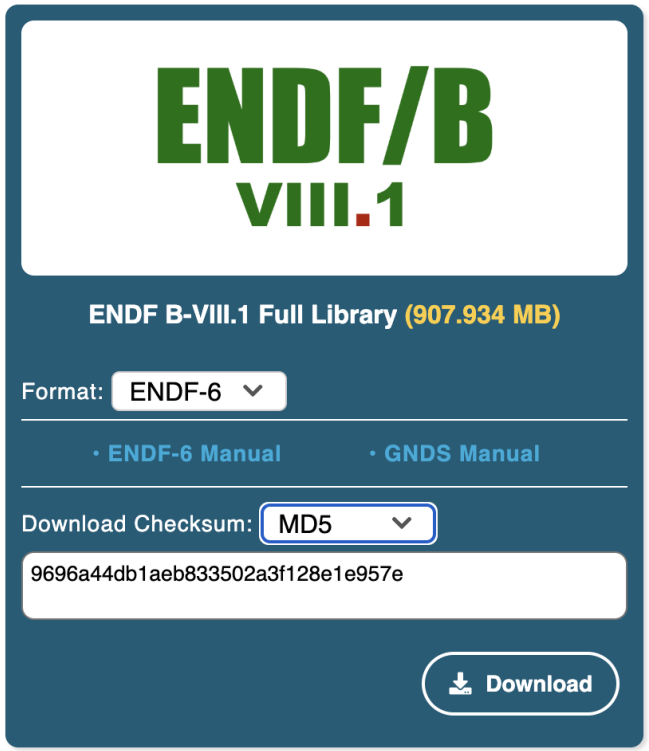
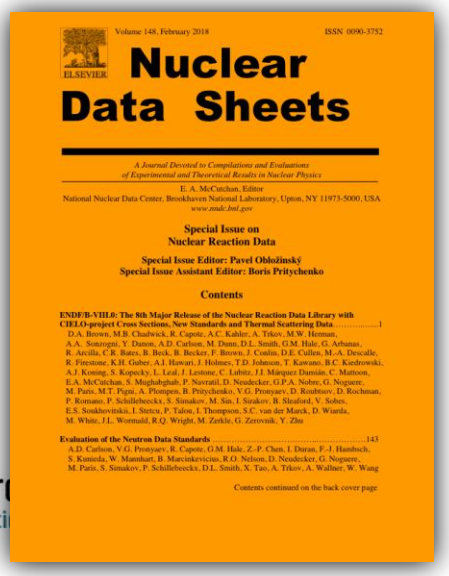
The Latest and Greatest

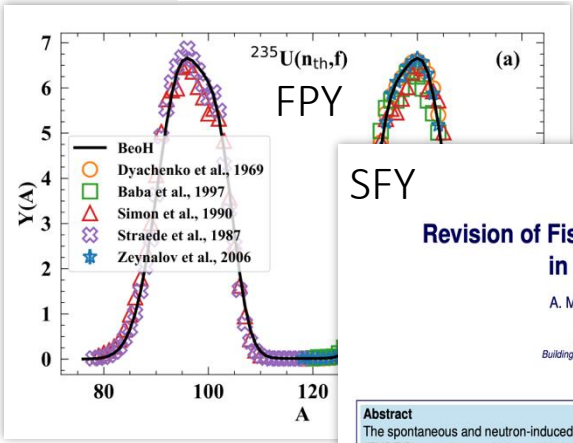
- Big paper to show up soon
- In addition to coordination role, BNL develops evaluations that fill notable gaps in programmatic coverage like structural materials, decay and FPY

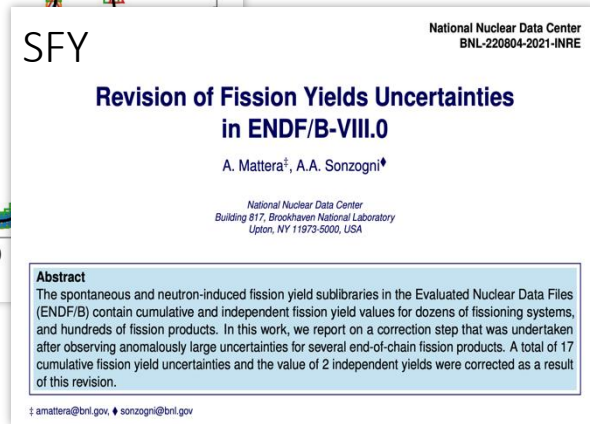
✓ August 30, 2024





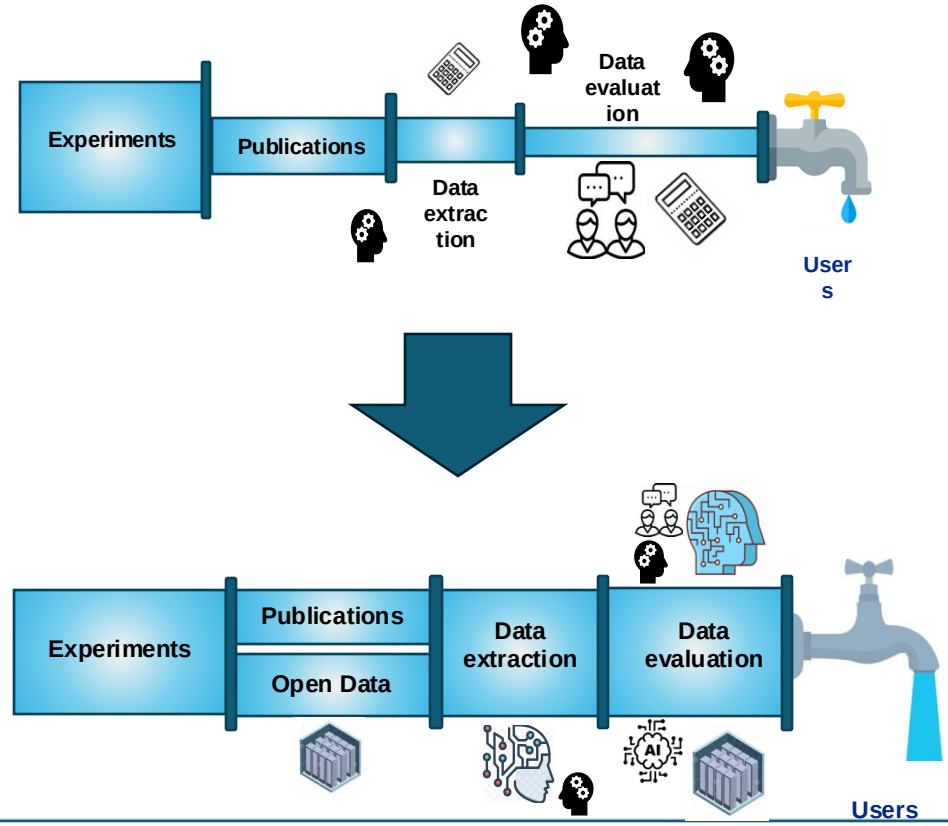
Once we release files, then they are integrated into codes





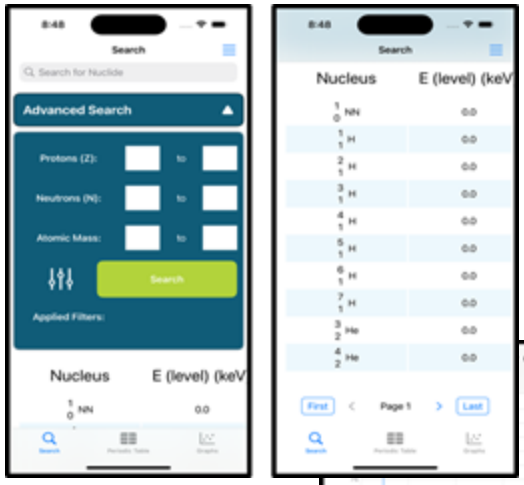
NNDC Initiatives

Integrating data and getting that data to users faster



NNDC Mobile Apps

- Offline, search-able access to NNDC data
  - Nuclear Wallet Cards
    - Ground- and isomer-state observable properties
  - CapGam
    - Gamma ray energies from thermal neutron capture
- Currently available on Google Play Store
- iOS versions created by SULI student Hamnah Irfan
  - [Currently applying to publish on App Store]



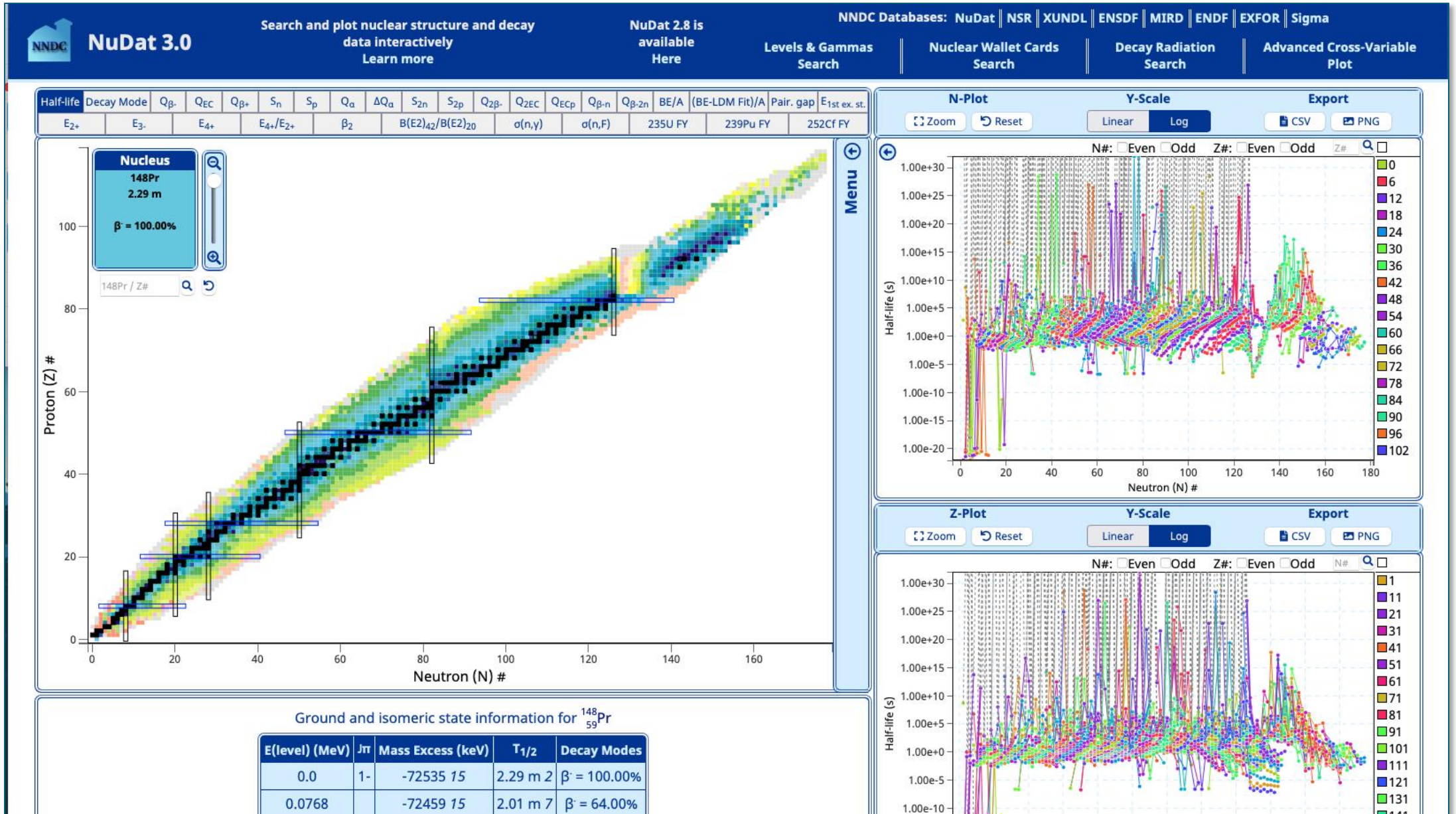
Wallet Cards

CapGam

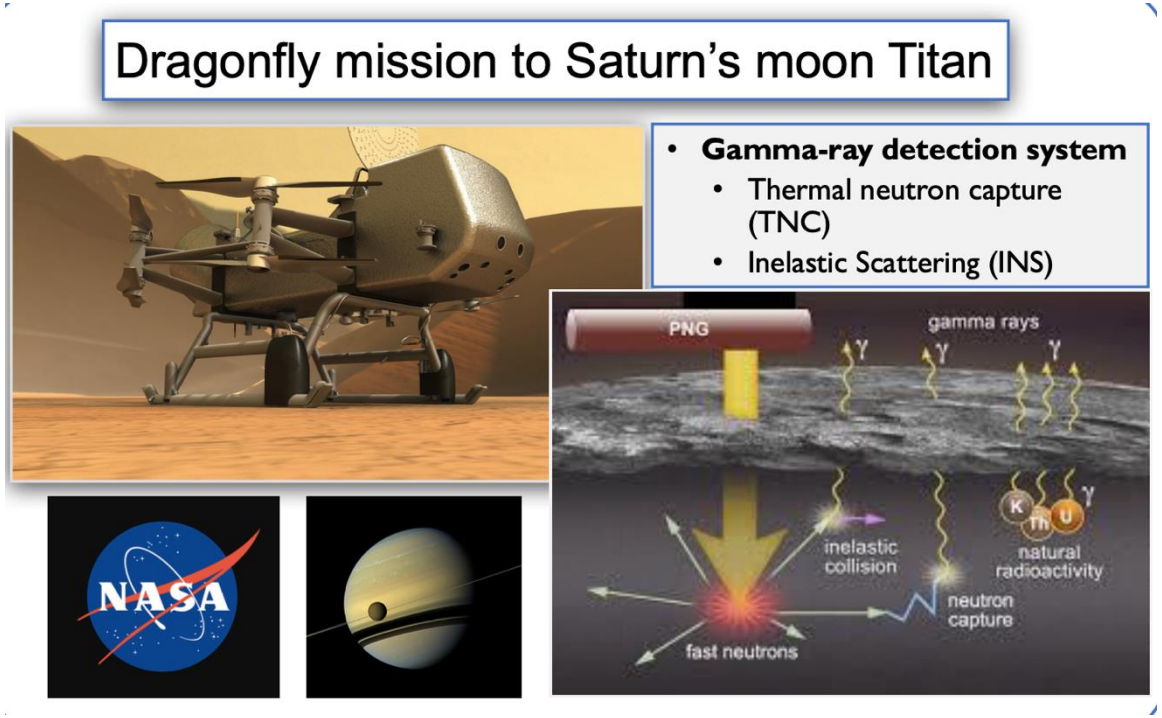
Bibliographic data: www.nndc.bnl.gov/nsr/

Great environment for Artificial Intelligence !!

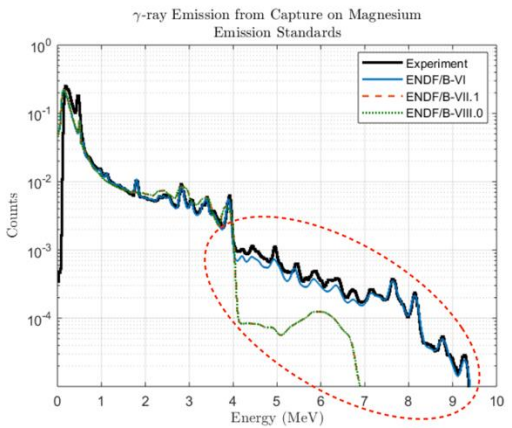
www.nndc.bnl.gov/nudat3

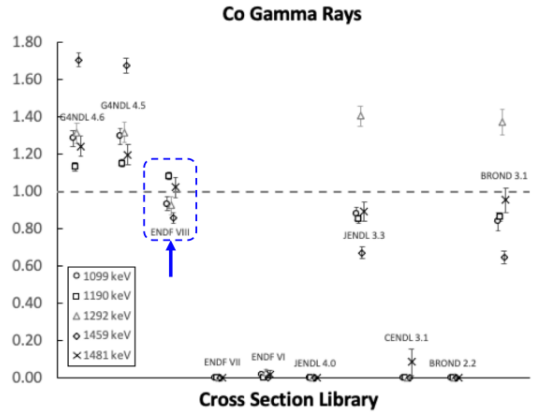


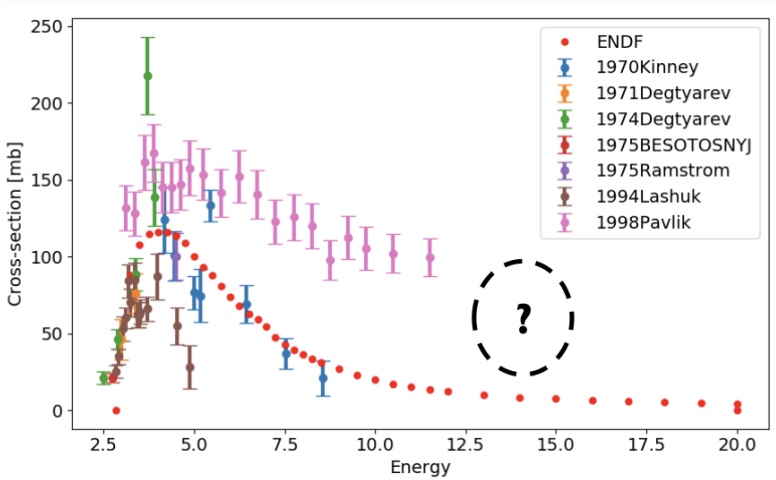
Not everything is shining … we have a lot to do



From Patrick Peplowski talk @DNP/NNDC







** Plots taken from Unzueta's and Mauborgne's talks in WANDA 2020*

- **Active Interrogation with fast neutron beams;**
  En = 14 MeV
- **Capture, Inelastic and Decay Gammas = Nuclear fingerprints**
- **Subject to**
  - Thorough experimental knowledge; Precise models and evaluations; Incorporation of data into evaluated files;

Planetary Nuclear Spectroscopy:
Space exploration!

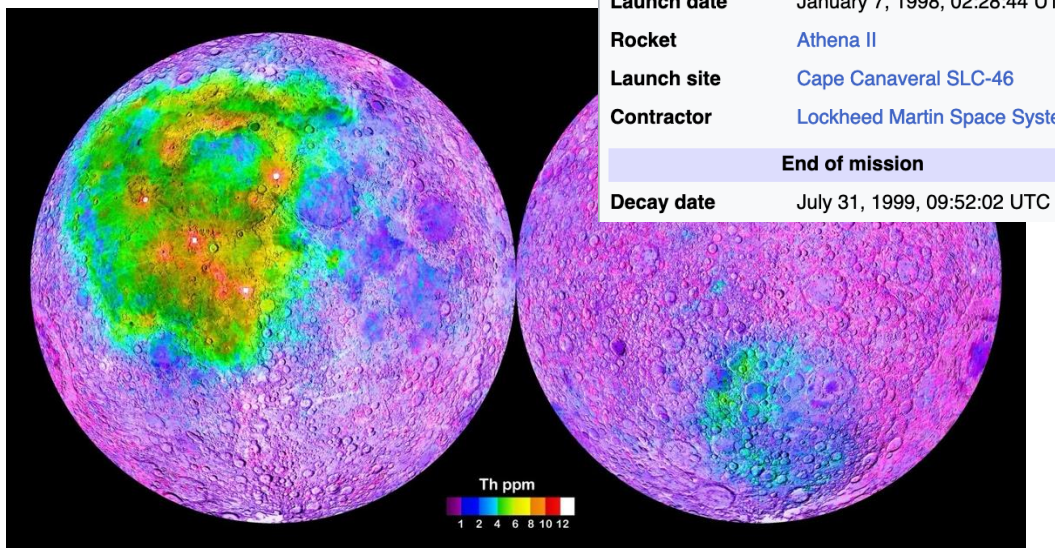
- **Planetary gamma-ray spectroscopy** via **A**ctive **I**nterrogation (AI) is an established technique for characterizing the surface composition of planets from orbit.
  - ➢ The success of **AI** depends on quality of **evaluated nuclear data**:

- NASA currently has numerous active and upcoming investigations valued at >$100M.

- **<u>Upcoming Missions</u>**:
- LunaH Map (2022)
- Psyche (2023),VIPER (2023)
- MMX (2024)
- **Dragonfly (2026)**
- Commercial Lunar Payload Services (multiple payloads/missions, 2022+)

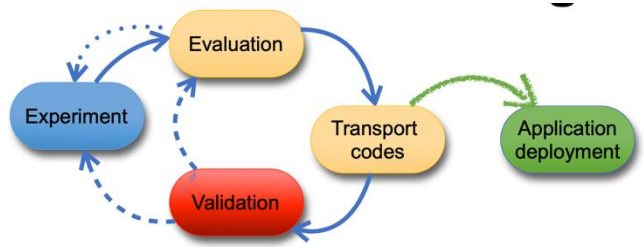
One of the first

Start of mission	
Launch date	January 7, 1998, 02:28:44 UTC[1]
Rocket	Athena II
Launch site	Cape Canaveral SLC-46
Contractor	Lockheed Martin Space Systems
End of mission	
Decay date	July 31, 1999, 09:52:02 UTC

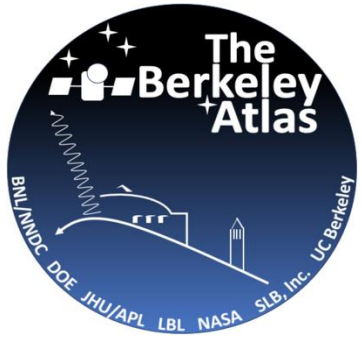


Thorium concentrations on the Moon, as mapped by Lunar Prospector.

We are currently partnering to improve our gamma-ray libraries



- **The 14 MeV Berkeley Atlas**
  - Dedicated campaign of 14-MeV (n,n′γ) measurements
  >24 isotopes and >35 γ's



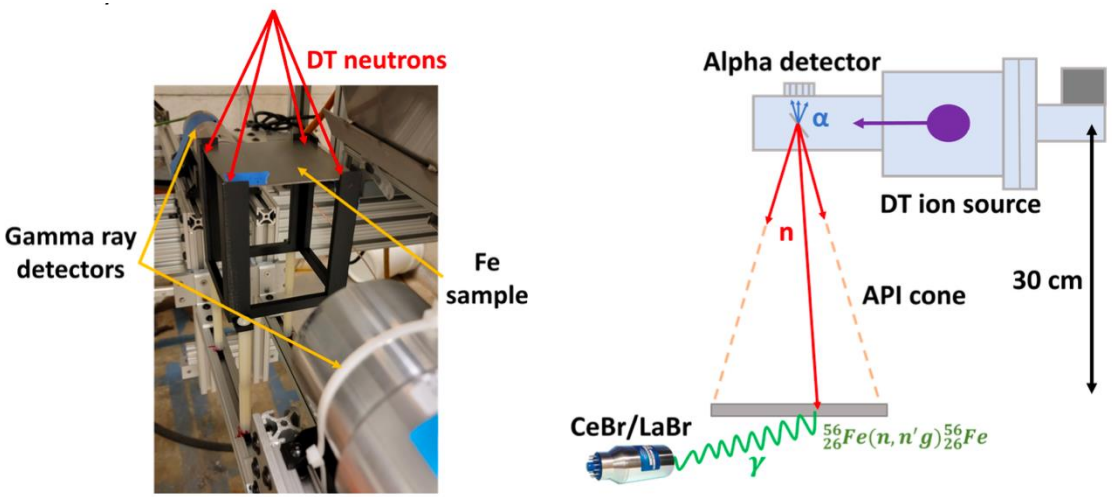


Figure 8: Actual (left) and schematic (right) Experimental setup showing the placement of both an iron sample relative to the neutron source and the gamma-ray detectors.

Team

Dr. Mauricio Ayllon Unzueta
Lawrence Berkeley National Laboratory

Dr. Lee Bernstein
UC Berkeley / LBNL

Dr. David Brown
Brookhaven National Laboratory

Dr. Emanuel Chimanski
Brookhaven National Laboratory

Joe Henderson
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Dr. Patrick Peplowski
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Dr. Arun Persaud
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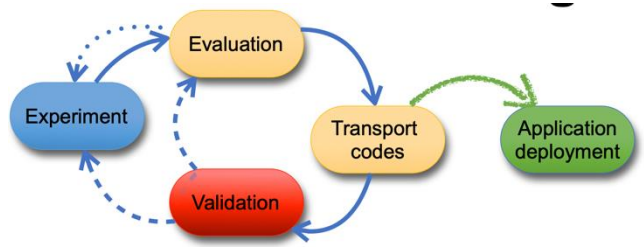
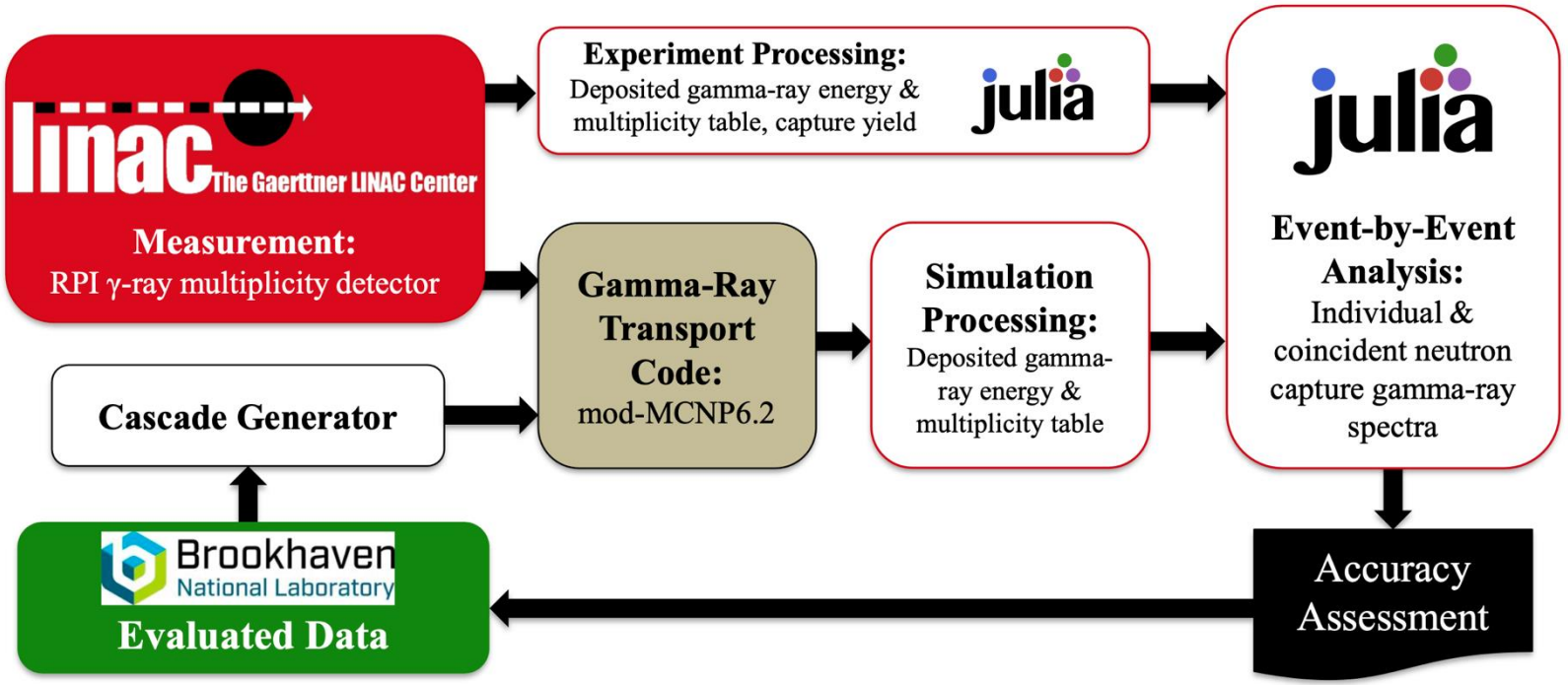
Dr. Jack Wilson
Johns Hopkins Applied Physics Laboratory

We are currently partnering to improve our gamma-ray libraries



- **Also improving neutron capture γ-rays**

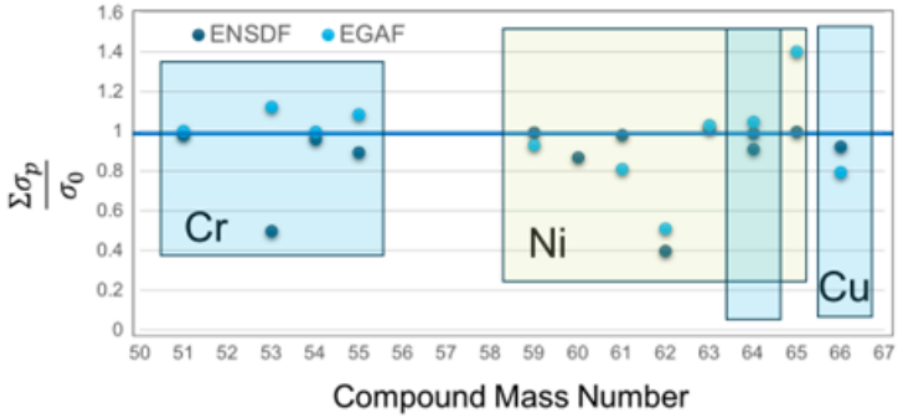
  - Develop methodology and provide data for benchmark qualifications



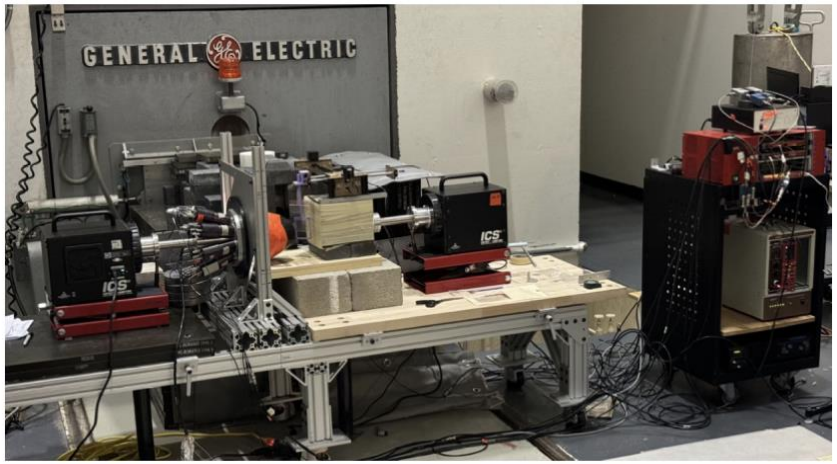
Rensselaer Polytechnic Institute:
Yaron Danon – PI
Katelyn Keparutis – Graduate Student
Ian Parker – Graduate Student
Brookhaven National Laboratory:
David Brown
Emanuel Chimanski
Naval Nuclear Laboratory:
Devin Barry
Amanda Lewis

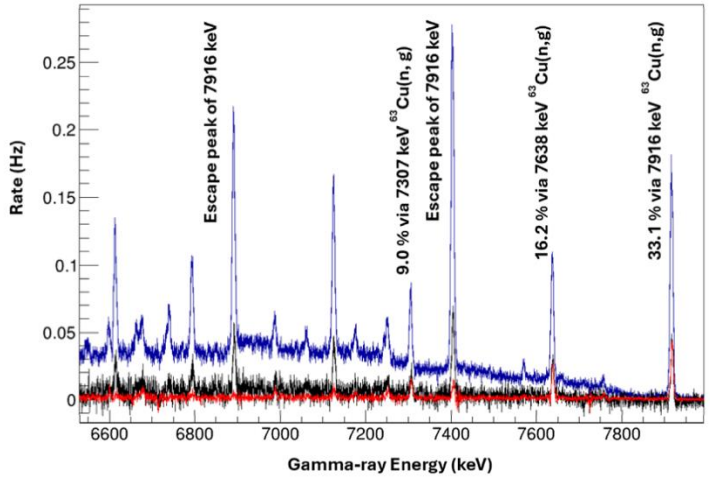
FAIR grant with UMASS Lowell

Improving thermal neutron capture data for ENSDF & ENDF



^{Nat}Cu(n,g)





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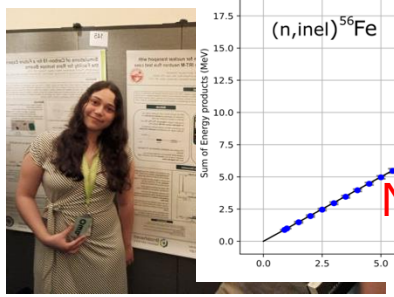
BNL led project GRIN (Gamma-Ray Induced By Neutron) just finished:

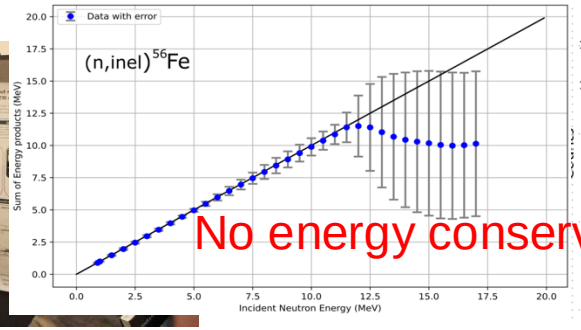
Updating γ-ray production in ENDF-6 files

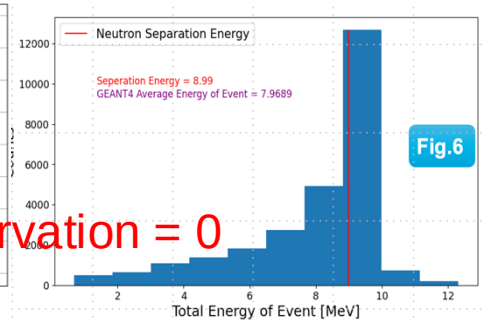
https://git.nndc.bnl.gov/grin/grin-formatter

- ✓ Automates upgrades and updates to γ rays, level and branching ratios.
- ✓ Ensures energy conservation

Nuclear Transport with Geant4 and ENDF







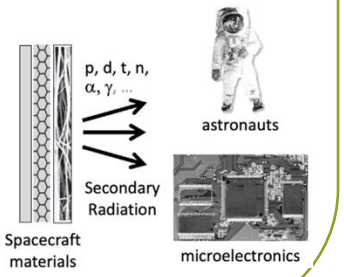
Krystine Rodriguez (UPR – Puerto Rico)

- Completed report (BNL-224447-2023-INRE) outlining issues and recommended remediation actions with capture and inelastic γ-rays
- Python packages for data processing/formatting:
  - pyEGAF: processes and manipulates EGAF data sets
  - grin_formatter: updates and formats γ-rays in ENDF-6 or GNDS.
- **GIDI+ API is working in GEANT4**.
  We can now make correlated γ-ray emissions with event-by-event precision
- Manuscript with details and proof-of-concept on enabling inline γ-ray cascades to be submitted to NIM.

We organized a satellite Meeting (@DNP2023 : Division of Nuclear Physics)

- Space exploration requires efforts in the **"nuclear data pipeline"**

- Theory
- Transport codes
- Radiation Damage
- Evaluations
- Measurements
- Data needs



Announcement of the Satellite Meeting at the 2023 Fall Meeting of the Division of Nuclear Physics of the American Physical Society and the Physical Society of Japan:

Topic: Nuclear Data for Space Applications

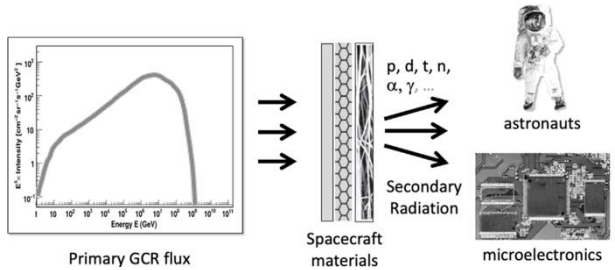
- 8 invited + contributed talks

Nagoya University, Johns Hopkins University Applied Physics Lab, NASA, Catholic University of America, Chubu University, NASA Langley Research Center ,Tokyo Institute of Technology, Lawrence Berkeley National Laboratory, J-PARC, JAEA, UC Berkeley, Los Alamos National Laboratory, UC Davis, IAEA

Nuclear Data and Space Applications

Shielding and Space Radiation

Stopping Powers for Secondary Particles[2]



Adapted from
Smith, *et al.* Front. Astron. Space Sci. (2023)

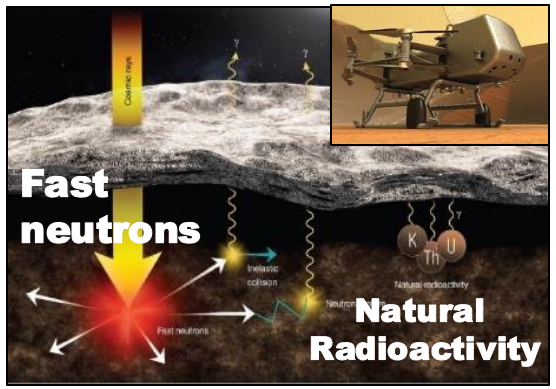
Interplanetary Astronaut Dose Considerations[1]

~ **100 MeV/n - 10 GeV/n**
- Projectile **fragmentation** **partial** and **total cross-sections**.

[1]J. Norbury et al., Rad. Meas. (2012)
[2]J. Osheroff *et al.*, IEEE Trans. (2021)

Active Interrogation

Fast neutrons (14 MeV) (DT) generators

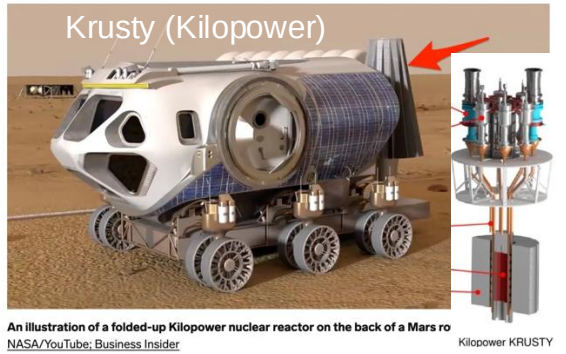


Inelastic, Capture and Decay Gammas (nuclear fingerprints)

C. Romano *et al.*, WANDA 2020 Final Report. ORNL/TM-2020/1617 (2020).
P. Peplowski numerous

Nuclear Propulsion/Power

Fission-powered rockets



Cross Section data already needed for powerplants

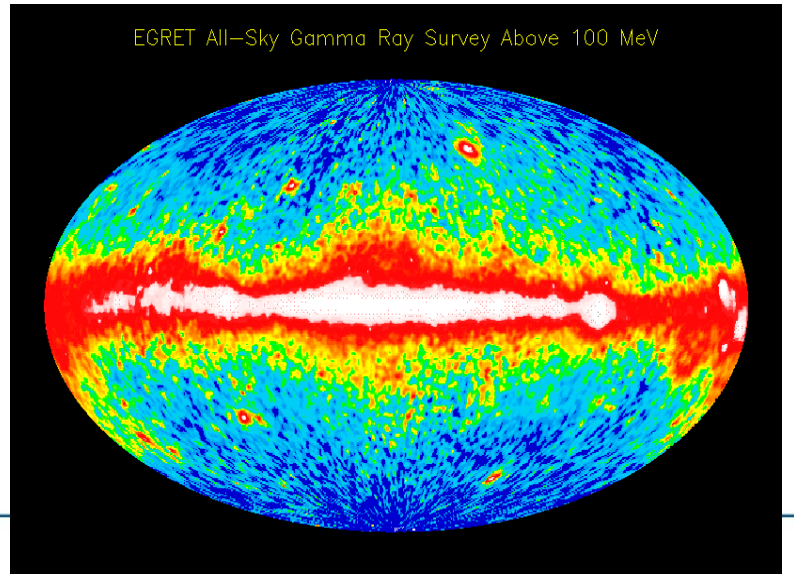
New: Spin Polarization for **Fusion** Propulsion[1]
- Larger cross-section (facilitates fusion ignition). Provides direction for reaction products (better trust, reduces weight)

[1]L. Baylor *et al* 2023 *Nucl. Fusion (2023)*

Above the Earth's atmosphere the GCRs provide a serious **impediment** to the **safety** and **viability** of space exploration.

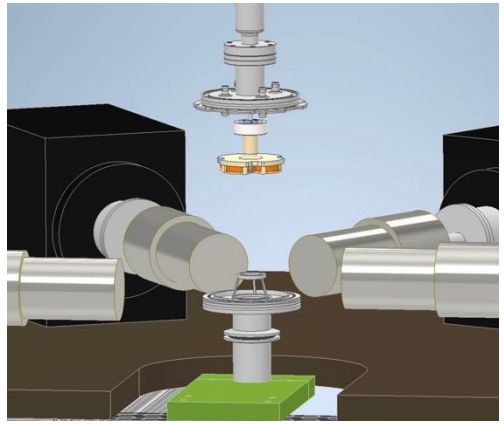
NNDC Initiatives

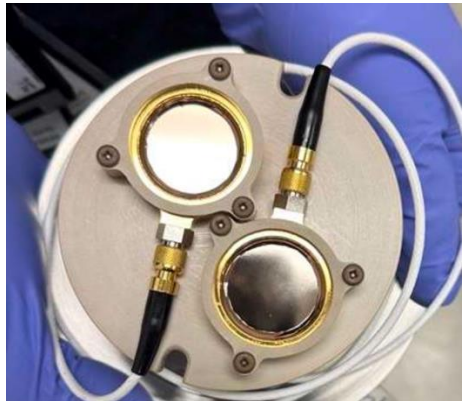
Going to higher energies

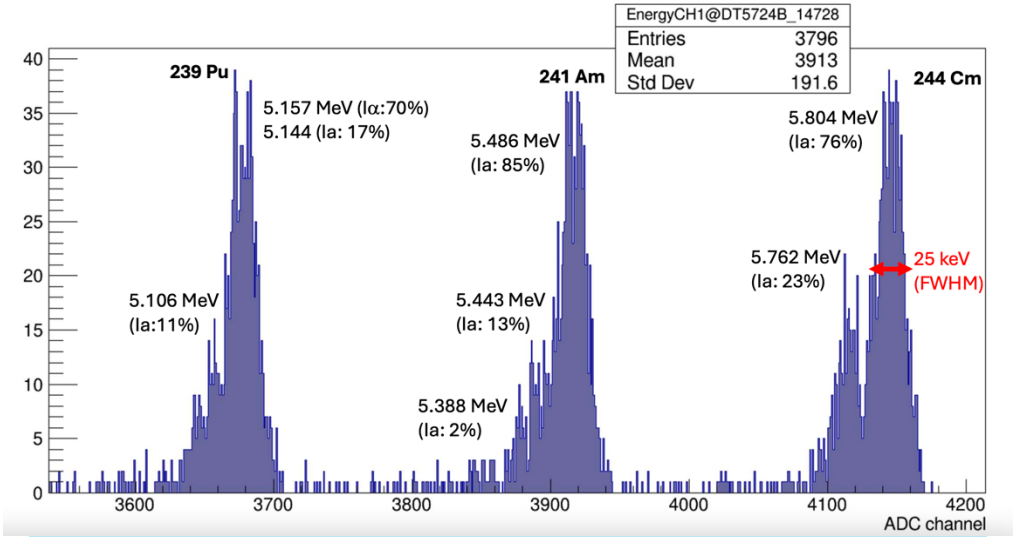


NNDC In-house Decay Measurements

α – gamma spectroscopy system complete



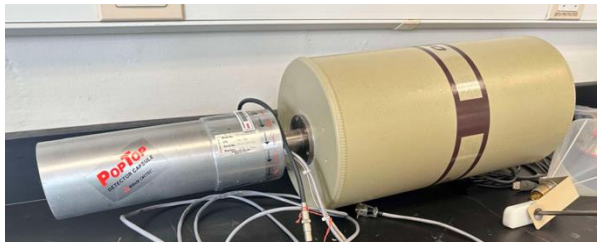




Measurements in progress of ^{225}Ac (Actinium): alpha therapy

Experimental Capabilities

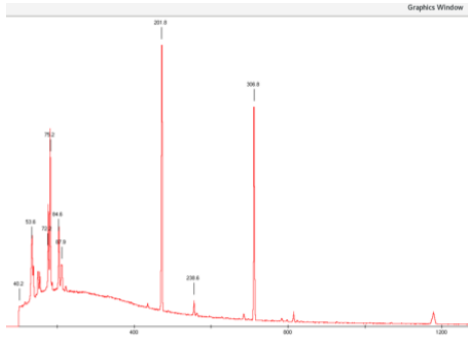
- 10 HPGe detectors
- 2 LEPS detectors
- 15 NaI detectors
- Low background well shield
- Electronics, cables, etc



Follow on LDRD from BNL to

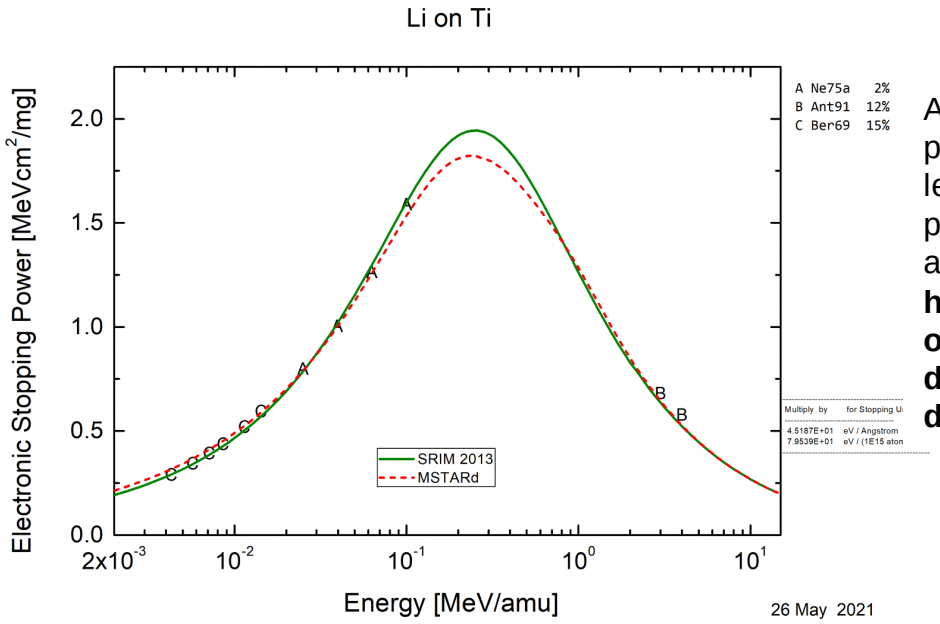
- Construct pumping/annealing station
- Purchase 2nd DAQ, sources, misc bits

Measurement of ^{176}Lu $T_{1/2}$ in progress



Ion stopping power measurements

- The **stopping power of ions in matter** is critical information **nuclear science, radiotherapeutics, radiation shielding**
- Data on stopping powers are sparse or non-existent for many materials, as shown in the figure on the right
- The NNDC is setting up a program to measure stopping powers of ions in various materials to address this need



A typical stopping-power curve. The letters indicate data points while the lines are calculations. **Note how the predictions of the peak height differ due to lack of data**.

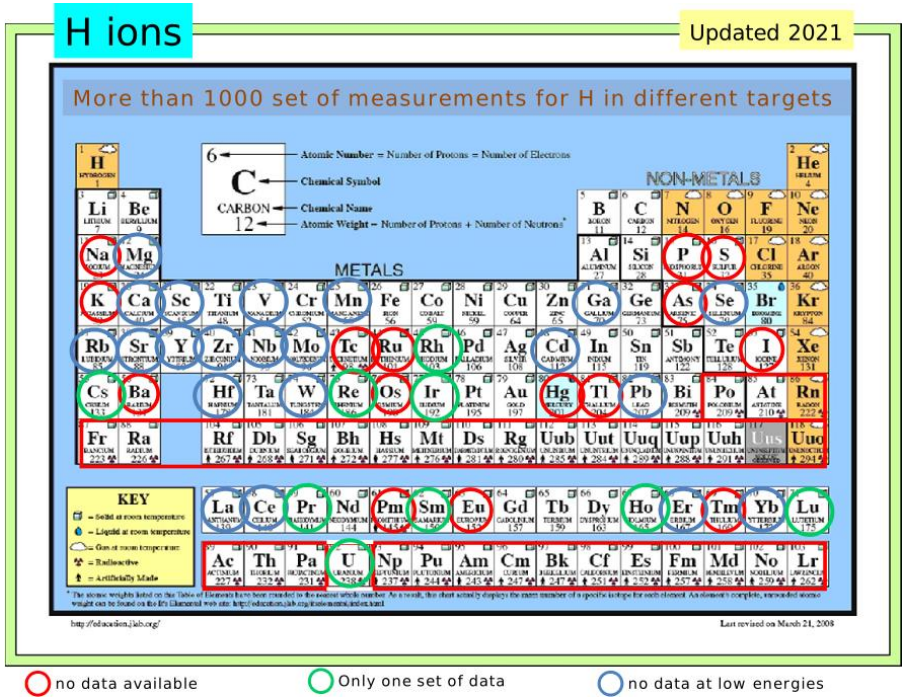
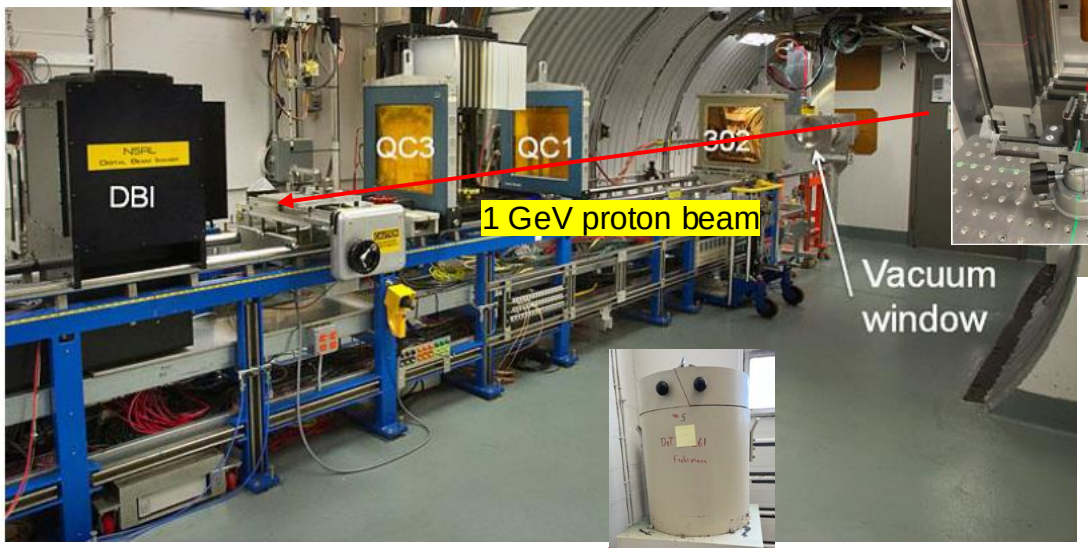


Figure from talk by Claudia Montanari at WANDA2022. Circles indicate elements for which there is little to no data for the stopping power of protons.

1 year LDRD to demonstrate feasibility of measurements.
PI: C. Morse

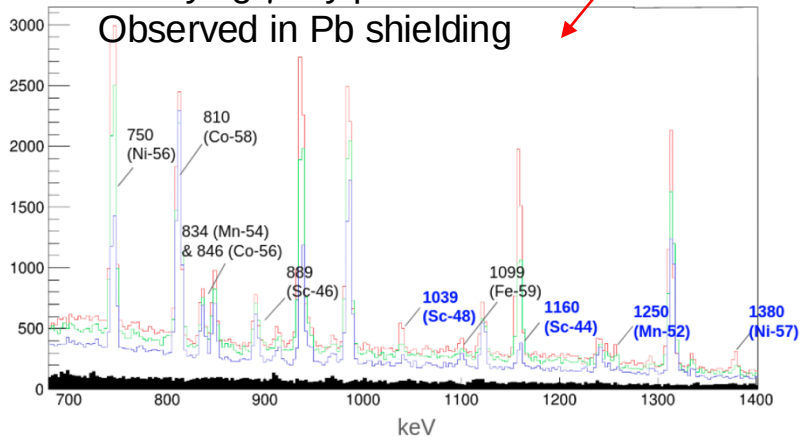
High energy proton spallation cross section measurements at NASA beamline at BNL

- ***NNDC intern, Daniel Quinter***, analyzed the data and determined cross sections *p*+Cu → X via activation (β-decay γ-ray measurements)



^{nat}Cu target

Decaying γ-ray peaks with time
Observed in Pb shielding



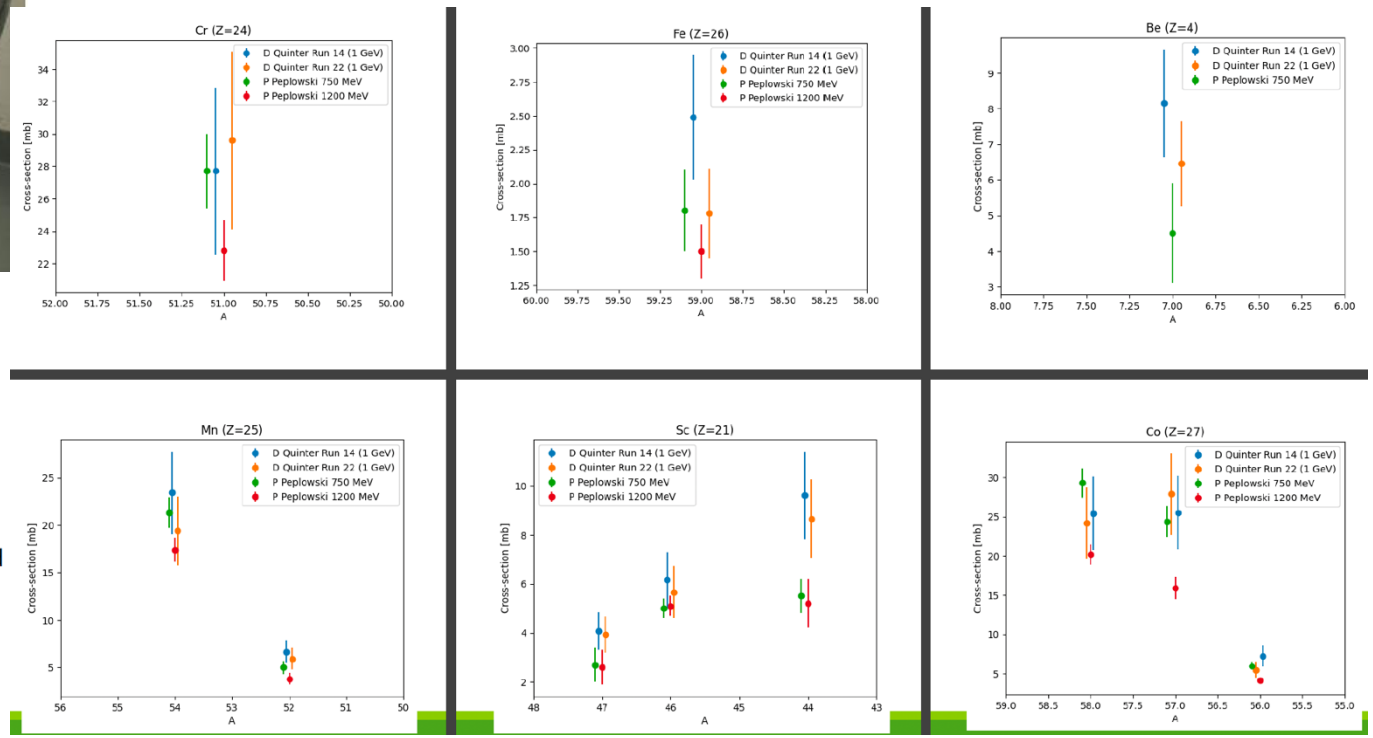
Time since irradiation

= 5 days

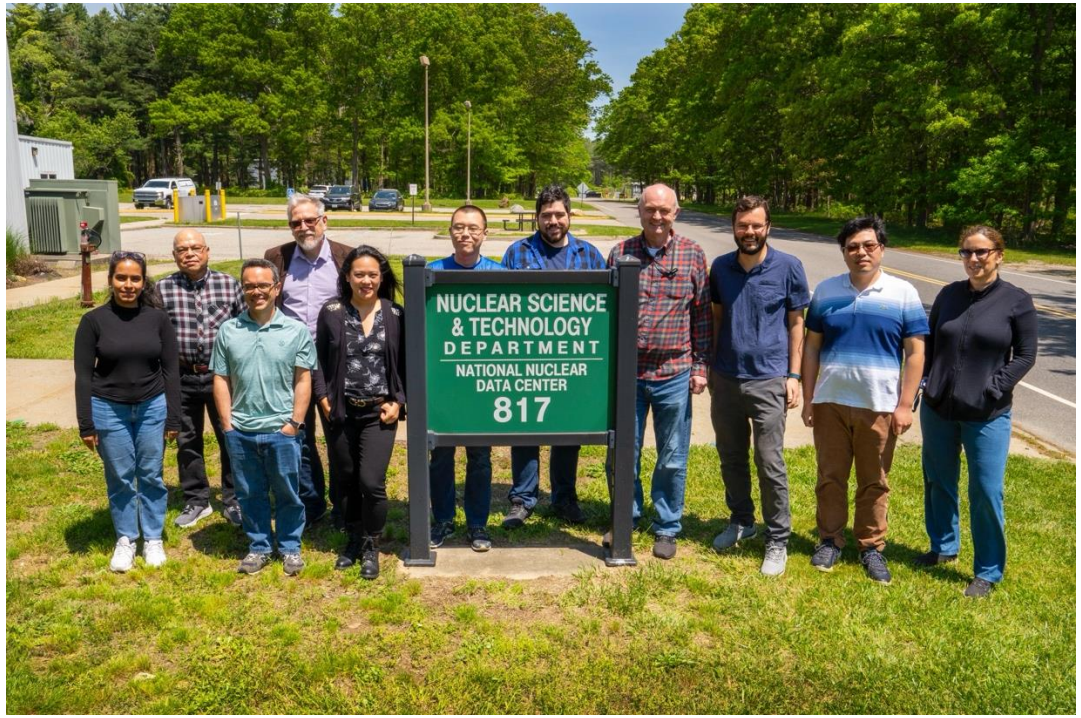
= 6 days

= 8 days

= Background



FY24 Staffing



- **For FY 24, the NNDC supported**
- 3 IT professionals (**Arcilla**, **Mason,** & **Shu**),
- 3 administrative staff (**Dunn**, Krejci, & Frejka)
- 11 permanent scientists (Brown, Chimanski, Coles, Mattera, Morse, Nobre, Ota, Ricard, Sonzogni, Pritychenko, & **Wu**)
- 2 postdocs (Kim & Waniganeththi)
- 3 contractors (Gritzay, Gurdal, & Symochko)

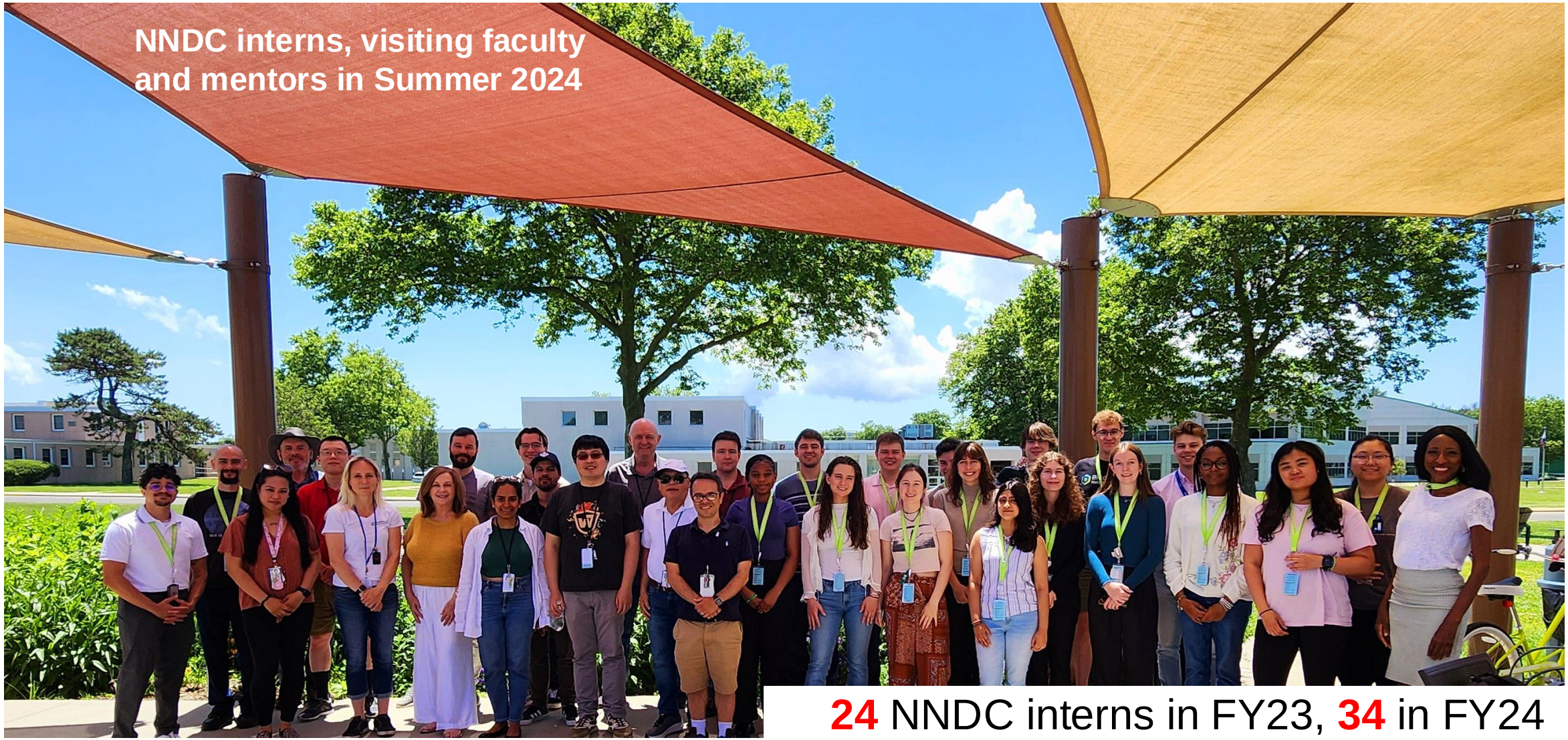
Legend

NNDC member, partly funded by USNDP

NNDC member, fully funded by USNDP

Non-NNDC member, partly funded by USNDP

Training the next generation workforce



24 NNDC interns in FY23, **34** in FY24

142 interns since 2014 | 61% from URG

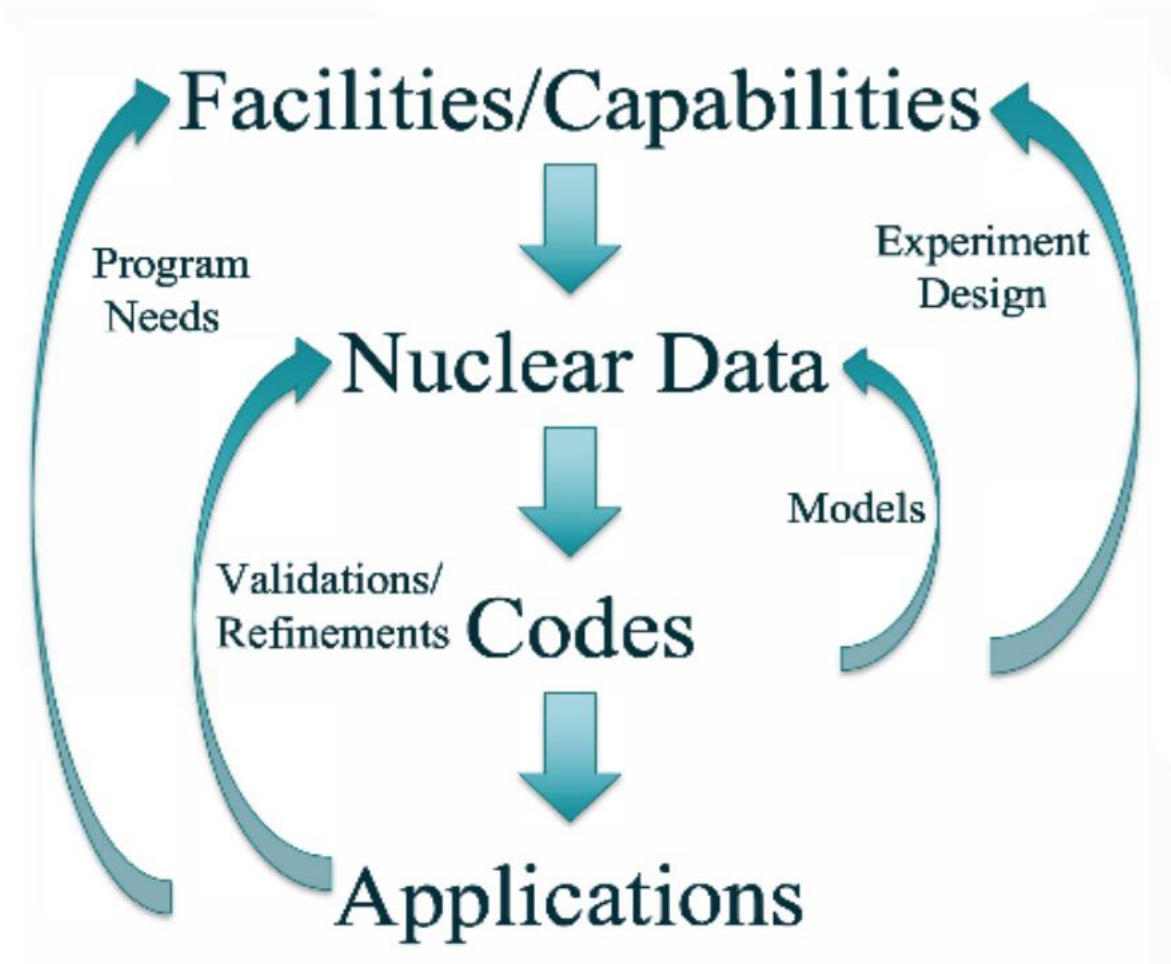
Brookhaven National Laboratory

Getting the word out about nuclear data

FY23 also saw completion of NP Long Range Plan

Key takeaways:

- *Nuclear data aligns with the NP community priorities*
- Chapter 11 is devoted to us!



National Nuclear Data Center

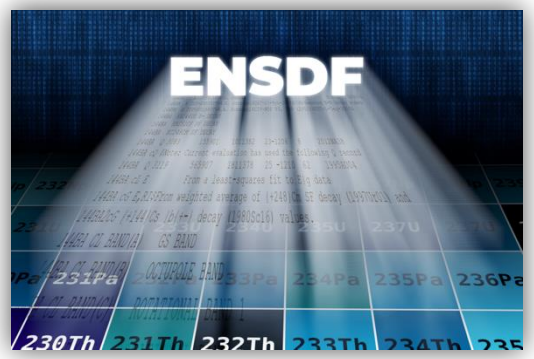
U.S. DEPARTMENT OF ENERGY | Office of Science

Maintaining and improving nuclear data for world-wide use

Nuclear Structure and Decay

Evaluated Nuclear Structure Data File (ENSDF)

One and only database of recommended values derived from all published experimental nuclear structure and decay data.



Experimental Unevaluated Nuclear Data List (XUNDL)

Compiled nuclear structure and decay data from recently published articles

Precision measurements of decay radiation properties

Nuclear Reactions

Evaluated Nuclear Data File (ENDF)

Recommended neutron reaction data for all nuclei relevant for nuclear science and technology

ENDF/B VIII.1

CSEWG Cross Section Evaluation Working Group

Experimental Nuclear Reaction Data (EXFOR)

World's only repository of experimental nuclear reaction data

Thank you

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