Nuclear Data in Applications

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National Nuclear Data Center
Brookhaven National Laboratory, NY USA
Nuclear Data Program
Link between basic science and applications

Nuclear Data Community needs data:
✦ complete
✦ organized
✦ traceable
✦ readable

Nuclear Science Community
• experiments
• theory

Application Community
needs data:
✦ complete
✦ organized
✦ traceable
✦ readable

Nuclear Data Community
✦ compilation
✦ evaluation
✦ dissemination
✦ archival
Nuclear data as a utility

There is a vast source of data

Which is processed, separated and shipped to you

Although not the most exciting part, we can’t forget about the infrastructure

In a convenient and usable form
The USNDP’s primary goal is to get the highest quality data to users.

Science  Security  Isotopes  Energy

FRIB
Our work begins when data is (or should be) published

**Code development:** Actively develop codes that support our work

**Archive:** Seek “abandoned” data and archive it before it is lost

**Address gaps:** Perform targeted experiments to address gaps in databases
Data is compiled into databases

**Nuclear Science References (NSR):**
226,000 nuclear physics articles indexed according to content. 3,300 articles added in FY17 from 80 journals.

**EXFOR:** Compiled nuclear reaction data, originally only for neutron-induced. Data from 100 articles added in FY17.

**XUNDL:** Compiled nuclear structure and decay data. Data from 325 articles added in FY17.
The Nuclear Data Pipeline

Evaluate data by combining all information into recommended values

**ENSDF:** Recommended nuclear structure and decay data for all 3,325 known nuclides.

**ENDF:** Recommended particle transport and decay data, with a strong emphasis on neutron-induced reaction data.

**Atlas of Neutron Resonances:** 6th edition of the famed successor to BNL-325, contains neutron resonance parameters, thermal cross sections and average resonance parameters.
Horizontal Evaluations

Nuclear physics input for r-process nucleosynthesis

- Masses: define reaction path
- Half-lives: define shape
- Shell structure far off stability: defines position of abundance peaks
- Neutrons from β-delayed neutron emission or (γ,n): smoothing of abundance curve
- Neutron capture cross sections: smoothing of abundance curve
- Neutrino interaction cross sections: change neutron-richness of environment
- Fission parameters: recycling of material into fission peaks

Need experimental information for isotopes between reaction path and stability!

From I. Dillman

IAEA Nuclear Data Section
Reference Database for Beta-Delayed Neutron Emission Data

- Half-lives and β-delayed neutron emission last compiled by Rudstam 2002
- IAEA coordinated research project, evaluation led by B. Singh

https://www-nds.iaea.org/beta-delayed-neutron/database.html
Collaborate with nuclear data community to get data ready for users

**Processing:** Prepare data for use in application codes.

**Validation:** Test data in simulations of non-trivial, but well understood, nuclear systems.

**Quality Assurance:** The NNDC’s ADVANCE nuclear data continuous integration system ensures the quality of data by automatically testing each ENDF evaluation as soon as it is changed.
The Nuclear Data Pipeline

NuDat, SIGMA, EXFOR searches

Nuclear Data Sheets

www.nndc.bnl.gov
Web Dissemination

About 4.5 million per year

Japan Earthquake
Friday 3/11/2011

Top Retrievals by Country (FY2017)

- United States: 34%
- China: 9%
- Japan: 4%
- Germany: 7%
- Other countries: 31%

Number of Daily Nudat Retrievals

Days of March
Users of Nuclear Data

Applications, Applications and More Applications

- Nuclear Medicine
- Nuclear Power
- Detector Simulations
- Stockpile Stewardship
- Homeland Security
Users of Nuclear Data

Provides essential input for other basic science fields

Data are versatile

Astrophysics

Neutrino Physics
Transforming our vast body of data into something of beauty
Many Applications Involve Fission

- Fissile material, such as uranium or plutonium
- Neutrons are used to induce fission
- Products of fission: 2 lighter nuclei and a few neutrons
- New neutrons carry on, and on, and on the process
Yields of Fission Fragments

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Z, number of protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>136Ba</td>
<td></td>
</tr>
<tr>
<td>137Ba</td>
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<tr>
<td>138Ba</td>
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<td>139Ba</td>
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<table>
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<tr>
<th>Nuclide</th>
<th>Yields of Fission Fragments</th>
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<tbody>
<tr>
<td>135Cs</td>
<td>2.3E+6 Y</td>
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<tr>
<td>136Cs</td>
<td>13.04 D</td>
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<tr>
<td>137Cs</td>
<td>10.08 Y</td>
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<tr>
<td>138Cs</td>
<td>33.41 M</td>
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<tr>
<td>139Cs</td>
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<table>
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<tr>
<th>Nuclide</th>
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<tbody>
<tr>
<td>134Xe</td>
<td>&gt;5.8E+22 Y</td>
</tr>
<tr>
<td>135Xe</td>
<td>9.14 H</td>
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<tr>
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<th>Yields of Fission Fragments</th>
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</thead>
<tbody>
<tr>
<td>131I</td>
<td>20.83 H</td>
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<tr>
<td>134I</td>
<td>52.5 M</td>
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<tr>
<td>132Te</td>
<td>3.204 D</td>
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<td>12.5 M</td>
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In the fission of 235U, more than 800 nuclides are produced. The table above shows the yields of fission fragments for selected nuclides.
Energy released in beta decay

Electromagnetic (EM) = \( \Sigma \gamma E_\gamma + \Sigma \text{x-ray} E_{\text{x-ray}} \)

Light Particle (LP) = \( \Sigma \beta^- E_{\beta^-} + \Sigma \text{ce} E_{\text{ce}} + \Sigma \text{Auger} E_{\text{Auger}} \)

Total Energy = EM + LP + E_{\text{neutrino}} = Q(\beta^-)
Decay heat from a reactor

\[ DH(t) = \sum_i E_i \lambda_i N_i(t) \]

\( E_i \) = Decay energy \((\beta, \gamma\text{ or both})\)

\( \lambda_i \) = decay constant

\( N_i(t) \) = number of nuclei \( i \) at cooling time \( t \)

Essential for
- Reactor control
- Shut down
- Post processing of fuel
But most things aren’t simple

Incomplete decay schemes:
- Smaller gamma-ray energies
- Larger beta energies
- 1st realized by Hardy in 1970's
- Termed Pandemonium effect

Actual  \[ Z,A \]  \( \beta^- \)  \( Z+1,A \)  

Weak gammas difficult to place in decay scheme

Observed  \[ Z,A \]  \( Z+1,A \)

New RIB facilities + New Total Absorption Gamma-ray Spectrometers (TAGS)

Will soon address these issues
Incorporating TAGS data

- WPEC-Subgroup (2006) identified 22 “high priority” nuclei

- New TAGS data on 7 nuclei from Valencia collaboration
Lots of room for improvement!!
And now for something completely different ...
Neutrino Oscillations

\[ |\nu_\alpha\rangle = \sum U_{\alpha i}^* |\nu_i\rangle \]

\[ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin \theta_{13} & \cos \theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2 + i\beta} \end{pmatrix} \]

\[ \theta_{23} = 40.4^\circ + 0.8^\circ \\ 1.8^\circ \]

\[ \theta_{13} = ?? \]

\[ \theta_{12} = 32.4^\circ \pm 0.8^\circ \]
The race to measure the final mixing angle

Intense source of $\theta_{13}$

$\theta_{13}$

Distance from reactor

Physicists in China Nail a Key Neutrino Measurement

Observation of Reactor Electron Antineutrinos Disappearance in the RENO Experiment
The story get more interesting

Analysis of all experiments close to reactors

Deficit in antineutrinos in all short baseline experiments

We observe 6% fewer electron antineutrinos from nuclear reactors at short distances, not accounted for the standard 3-flavor oscillation.

PHYSICAL REVIEW D 83, 073006 (2011)

Reactor antineutrino anomaly

G. Mention,¹ M. Fechner,¹ Th. Lasserre,¹,²,* Th. A. Mueller,³ D. Lhuillier,³ M. Cribier,¹,² and A. Letourneau³
And then the story got more interesting

Re-analysis + New Daya Bay results

Data/prediction = 0.946+0.022
And more interesting

The “bump”:

An excess of measured antineutrinos relative to predictions

New Physics???

News Particle Physics

Reactor data hint at existence of fourth neutrino

Deficit in antiparticle output exceeds theoretical expectations

By Ron Cowen 1:20PM, February 25, 2016

Ghost Finder: New results of experiments at the Daya Bay neutrino detector (walls lined with photomultiplier tubes, shown) hint at the existence of a lightweight sterile neutrino, about one-millionth the mass of an electron.
What are the implications?

Many possible explanations

• Predicted Antineutrino spectrum is incorrect
• Experimental bias in all experiments
• New physics at short baselines
  • Existence of one (or more) neutrinos beyond the standard model
Understanding reactor $\nu_e$ flux is nuclear physics

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<tr>
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<th>N, number of neutrons</th>
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<tbody>
<tr>
<td>136Ba</td>
<td>137Ba</td>
</tr>
<tr>
<td>STABLE</td>
<td>STABLE</td>
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<tr>
<td>7.854 %</td>
<td>11.232 %</td>
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<tr>
<td>2.4E-8</td>
<td>1.3E-6</td>
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<tr>
<td>2.3E+6 Y</td>
<td>1.3E+6 Y</td>
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<tr>
<td>β-: 100.00 %</td>
<td>β-: 100.00 %</td>
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<tr>
<td>2.5E-6</td>
<td>2.8E-6</td>
</tr>
<tr>
<td>134Xe</td>
<td>&gt;5.8E+22 Y</td>
</tr>
<tr>
<td>9.14 H</td>
<td>&gt;2.4E+21 Y</td>
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<tr>
<td>β-: 100.00 %</td>
<td>β-: 100.00 %</td>
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<tr>
<td>2.5E-4</td>
<td>0.00178</td>
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<td>133I</td>
<td>134I</td>
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<tr>
<td>20.83 M</td>
<td>6.58 M</td>
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<tr>
<td>β-: 100.00 %</td>
<td>β-: 100.00 %</td>
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<tr>
<td>8.5E-4</td>
<td>0.0036</td>
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<tr>
<td>132Te</td>
<td>133Te</td>
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<tr>
<td>3.204 D</td>
<td>12.5 M</td>
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<tr>
<td>β-: 100.00 %</td>
<td>β-: 100.00 %</td>
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<tr>
<td>0.0153</td>
<td>0.0299</td>
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</table>

A problem at the top of the nuclear data pyramid.

- Reactor
- Antineutrinos
- ENSDF
- ENDF
- XUNDL
- EXFOR

Brookhaven National Laboratory
Simple Example: $^{137}\text{Cs}$

$I(E) = N W (W^2 - 1)^{1/2}(W - W_0)^2 F(Z,W) C(Z,W)(1 + \delta)$
One approach to calculating the $\nu_e$ flux

Ab-initio Method or Summation Method

Individual Beta spectra

Fission Yields
Anti-neutrinos from reactors

Detection through inverse $\beta$ decay on proton

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

But cross section is tiny !!

\[ \langle \sigma \rangle \sim 10^{-16} \text{ mb} \]

Reactors are copious producers of antineutrinos

\[ \sim 5 \cdot 10^{20} \frac{\bar{\nu}_e}{s} \]

Reaction threshold : \( \sim 1.8 \text{ MeV} \)
Summation for $^{235}$U

Summation for $^{239}\text{Pu}$
Main Contributors at ~5 MeV

Top 10 contribute ~60% to the overall spectrum

New measurements underway based on these sensitivity studies
The anomaly, or not?

- Daya Bay measured the antineutrino yield as a function of $^{239}$Pu in the reactors.
- Measured $^{239}$Pu yield agrees with predictions.
- Measured $^{235}$U yield does NOT agree with predictions.
- If an anomaly is present, it should be present in both.

This analysis relies on one set of measurements from the 1980's.

Weird sterile neutrinos may not exist, suggest new data from nuclear reactors.
Abstract ends with:
‘An analysis of the antineutrino spectra that is based on a summation over all fission fragment $\beta$ decays, using nuclear database input, explains all of the features seen in the Daya Bay evolution data. However, this summation method still allows for an anomaly. We conclude that there is currently not enough information to use the antineutrino flux changes to rule out the possible existence of sterile neutrinos.’
Real “applied” uses for antineutrinos?
"In regard to nuclear proliferation and arms control, the fundamental problem is clear: Either we begin finding creative, outside-the-box solutions or the international nuclear safeguards regime will become obsolete."

- M. ElBaradei, then Director General of the IAEA

Washington Post, June 14, 2006

- Neutrinos go through everything
- Large investments in neutrino detection technology
- Understand neutrino flux from reactors
Exploit differences in signal

Different signal in:
- Shape
- Maxima
- Number

Can be used in non-proliferation and reactor monitoring

Advantages: Non-intrusive, “real-time” measurements
This sounds crazy... but it's not.

Many efforts:
- USA
- Canada
- Japan
- France
- Brazil
- Italy
- UK
- Korea
Watchman experiment

The New York Times

*How to Spot a Nuclear Bomb Program? Look for Ghostly Particles*

The Boulby mine in northeast England will be home to the Watchman experiment, which aims to
**Nuclear Medicine**

**Positron Emission Tomography (PET)**

- PET = positron emission tomography
- Radioactive positron emitters injected into body
- Usually attached to carrier molecule
- Radioactive source accumulates in areas of interest targeted by carrier molecules
- Position sensitive detector “rings” detect back-to-back 511keV annihilation gammas
- More decays from regions of higher concentration

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**Targeted Radionuclide Therapy**

- Ionizing radiation to kill cancer cells and shrink tumors
- Uses molecule labeled with radionuclide
- Beta, alpha or Auger electrons

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*Miller et. al. Angewandte Chem. Int. Ed. 47, 8998, 2008*

*M. Sadeghi et al., J Can Res Ther 2010;6:239*
Theranostic Radionuclides

- Simultaneous therapy and imaging
- Visualization of dose and distribution

A. Yordanova et al., Onco Targets Ther. 2017; 10: 4821

Over half were last studied >30 years ago!!
Capitalizing on advances in $\gamma$-ray spectroscopy

30 Years ago: 1-2 small detectors

Present: 10-100 detectors

Compton suppression

$\gamma\gamma$ coincidences
Gammasphere at Argonne National Lab

100 HPGe detectors
Compton-suppressed
Digital or analog DAQ
Starting point: \(^{82}\text{Rb}\) for Cardiac PET


\(2\ \text{Ge(Li)}\) detectors
The power of Gammasphere

Prior Singles

Gate on $2^+ \rightarrow 0^+$
Revised decay scheme for $^{82}$Rb

And so much more ...

- Stockpile Stewardship
- Isotope Production
- Nuclear Forensics
- Astrophysics
- Oil logging
- Waste disposal and transmutation
- ...