Applied Nuclear Science (and Nuclear Data)

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mccutchan@bnl.gov

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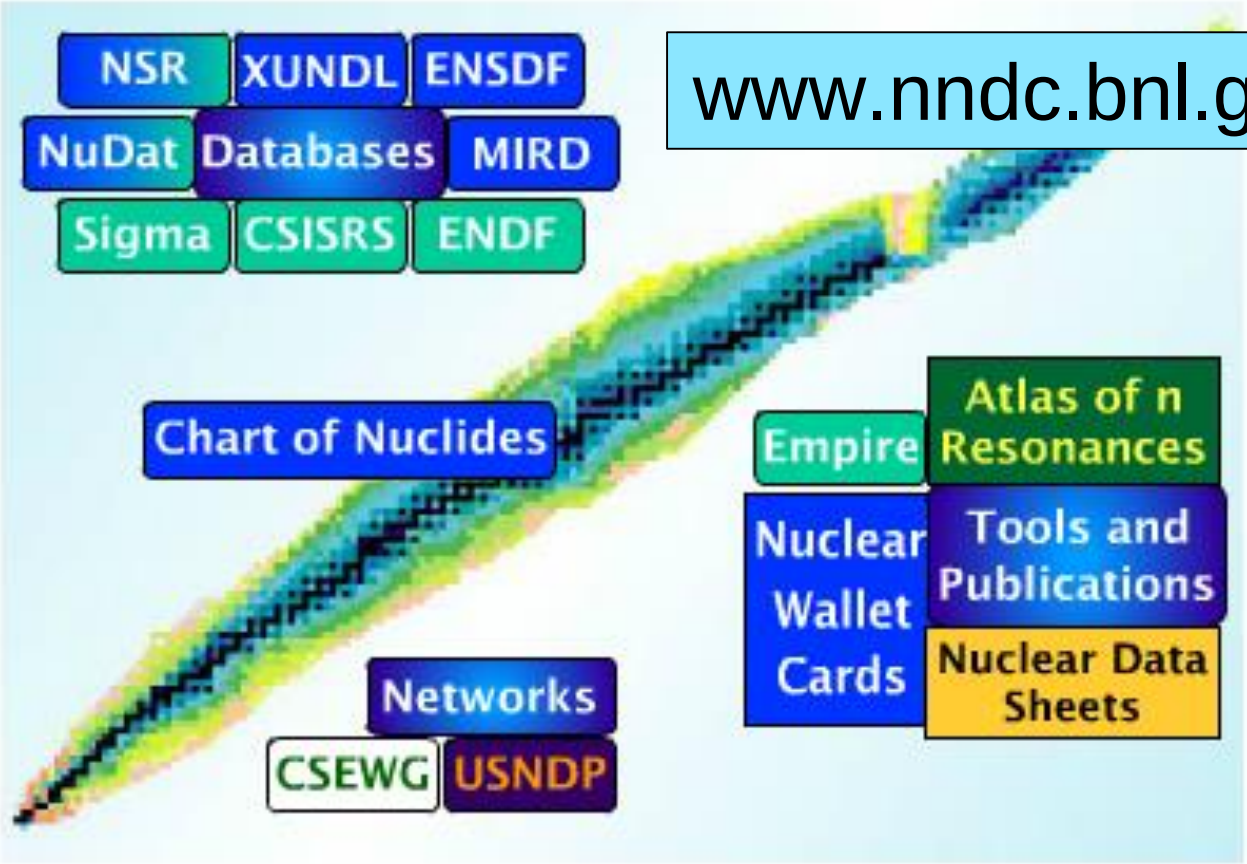
U.S. DEPARTMENT OF ENERGY

@BrookhavenLab

National Nuclear Data Center



www.nndc.bnl.gov

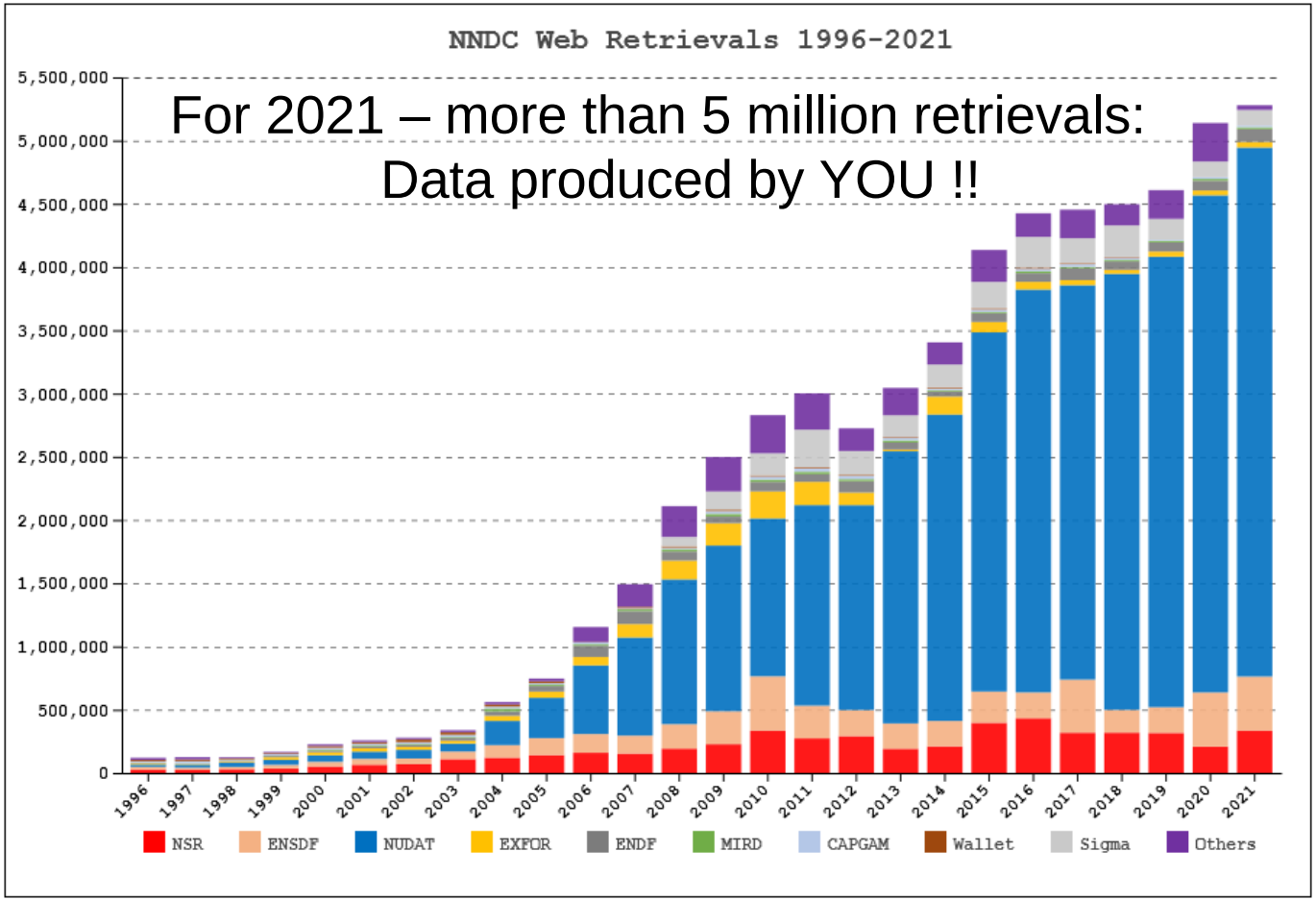
Brookha
National Labo

How many downloads of nuclear data per day? (just through the NNDC website)

a)150
b)1,500
c)15,000

Open Data Web Downloads

The Taylor Swift of Nuclear Physics?



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Nuclear Data Program

Link between basic science and applications

Nuclear Science Community

- experiments
- theory

Nuclear Data Community

- ✦ compilation
- ✦ evaluation
- ✦ dissemination
- ✦ archival

Applications Community

needs data:

- ✦ complete
- ✦ organized
- ✦ traceable
- ✦ readable

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The Nuclear Data Pipeline

70+ years of nuclear data measurements available

These are collected, processed, separated and shipped

In a convenient and usable form

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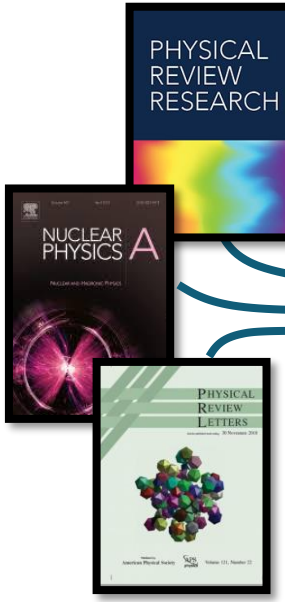
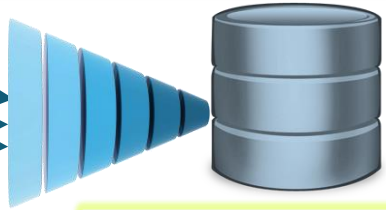
Nuclear Data Pipeline



Nuclear Science References
(bibliographical database)



- ~250,000 articles total
- ~3,000 articles per year
- Extract meta-data
- Web interface

I want to know about measurements of the half-life of ^{141}Te

- Publications are 95% source of data
  - Journals
  - Lab Reports
  - Theses
- Literature scanned on weekly basis

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Google Scholar

Te-141

About 862 results (**0.12** sec)

Radiochemical studies on the use of modified resins in the isolation and separation of Ce (III), Zr (IV), Hf (IV), Te (IV) and Nb (V)
FH El-Sweify, EAA El-Shazly… - Arab Journal of Nuclear …, 2007 - inis.iaea.org
[en] Comparative studies were carried out for further characterization of some modified resins and for the application of these modified resins in the isolation and separation of some …
Save Cite Cited by 1 Related articles All 2 versions

Sociodemografski profil sudionica u Kohortnoj studiji rođenih na istočnojadranskim otocima (CRIBS)
A Perinić Lewis, M Zajc Petranović, T Carić… - Hrvatski geografski …, 2019 - hrcak.srce.hr
… Uzorak čini 286 trudnica (145 s otoka Brača i Hvara **te 141** trudnica s kopna). Cilj je ove studije: 1) opisati glavna obilježja CRIBS uzorka, 2) usporediti uzorak s općom hrvatskom …
Save Cite Related articles All 2 versions

Determination of the Debye temperature of SnTe using the Mössbauer effect in 119Sn and 125Te
S Bukshpan - Solid State Communications, 1968 - Elsevier
The temperature dependence of the recoilless fraction in SnTe has been measured in 119 Sn and 125 Te nuclei in the range 85 < T < 250 K. Assuming a Debye model for the recoilless …
Save Cite Cited by 27 Related articles All 3 versions

[HTML] Imaging patterns in elastofibroma dorsi
M Battaglia, D Vanel, P Pollastri, A Balladelli… - European journal of …, 2009 - Elsevier
… Axial T1-weighted (TR/**TE 141**/7.5) spin echo MR images show a relatively well-defined homogeneous mass between the chest wall and the scapular tip with signal intensity similar to …
Save Cite Cited by 70 Related articles All 13 versions

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Web of Science

1 One-pot strategy for obtaining magnetic PMMA particles through ATRP using Fe(CO)(5) as co-initiator
Diacon, A; Rusen, E; (...); Tutunaru, O
Jun 5 2021 | Apr 2021 (Early Access) | EUROPEAN POLYMER JOURNAL 152
65 References
Related records

2 Mechanism of p… terpolymerizati… fabrication … nic crystals
Rusen, E; Mocanu, A…
Apr 5 2021 | Jan 202…
614
3 Citations
53 References
Enriched Cited…
This study presents … acrylamide) (NiPAM… reaction mechanism… …opyl … ratio on the
Related recor…

Nuclear Science References Search Result

2020WU04 Phys.Rev. C 101, 042801 (2020)

J.Wu, S.Nishimura, P.Moller, M.R.Mumpower, R.Lozeva, C.B.Moon, A[illegible]o
wne, R.Daido, P.Doornenbal, Y.F.Fang, M.Haroon, T.Isobe, H.S.Jung[illegible]P
atel, S.Rice, H.Sakurai, Y.Shimizu, L.Sinclair, P.-A.Soderstrom, T.Su[illegible], H.Watanabe

Keyworded description of the article

β-decay half-lives of 55 neutron-rich isotopes beyond the N = 82 shell gap

RADIOACTIVITY ^{134,135,136,137,138,139}Sn, ^{134,135,136,137,138,139,140,141,142}Sb, ^{137,138,139,140,141,142,143,144}Te, ^{140,141,142,143,144,145,146}I, ^{142,143,144,145,146,147,148}Xe, ^{145,146,147,148,149,150,151}Cs, ^{148,149,150,151,152,153}Ba, ^{151,152,153,154,155}La(β^-)[from ^{9}Be(^{238}U, F), E=345 MeV/nucleon, followed by separation of fragments using BigRIPS separator at RIBF-RIKEN]; measured β and γ radiations, half-lives by (implant)β and (implant)βγ correlations using the Wide range Active Silicon-Strip Stop per Array for Beta and ion (WAS3ABi) detection system and Euroball RIKEN Cluster Array (EURICA) of 84 Ge cluster detectors. Comparison with previously available experimental half-lives, and with theoretical calculations using FRDM+QRPA, KTUY+GT2, RHB+pn-RQRPA, and DF+CQRPA models. ^{141}Te(β^-); calculated half-life and Gamow-Teller strengths using FRDM+QRPA(2019) model, and compared with experimental data. Discussed and calculated effects of new half-life data on r-process abundance.

doi: 10.1103/PhysRevC.101.042801

Link to journal

Link to compiled data

Citations: PlumX Metrics

*Data from this article have been entered in the **XUNDL** database. For more information, click here.*

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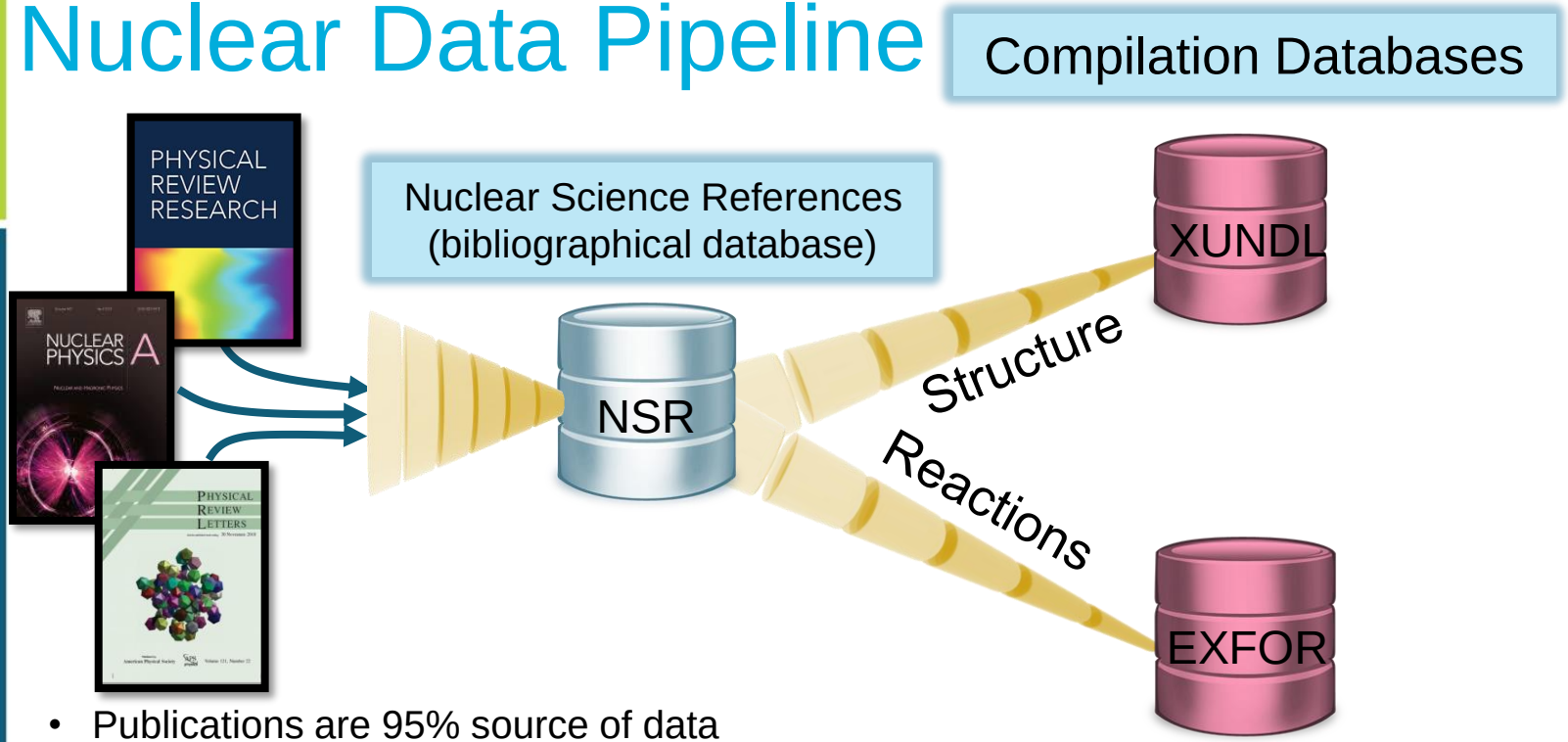
Nuclear Data Pipeline



- Publications are 95% source of data
  - Journals
  - Lab Reports
  - Theses
- Literature scanned on weekly basis

- Extraction of meta- and numerical data
- Data converted to database format
- Several consistency checks of data

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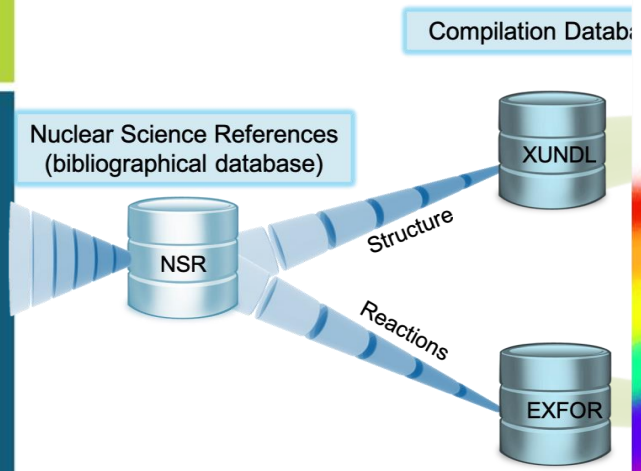
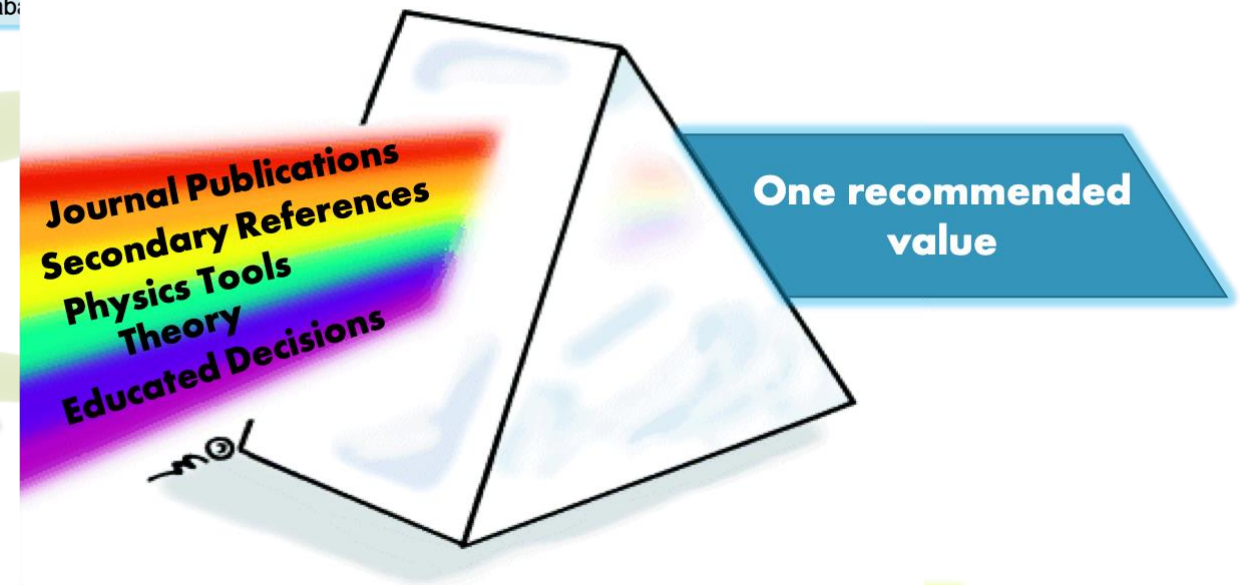
Nuclear Data Pipeline





- Critical assessment of all available experimental data
- Provide recommended values
- Testing and Validation important component
- Structure and reaction data not independent

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Nuclear Structure Database (ENSDF)

Quantum mechanical system with 1 to hundreds of interacting nucleons

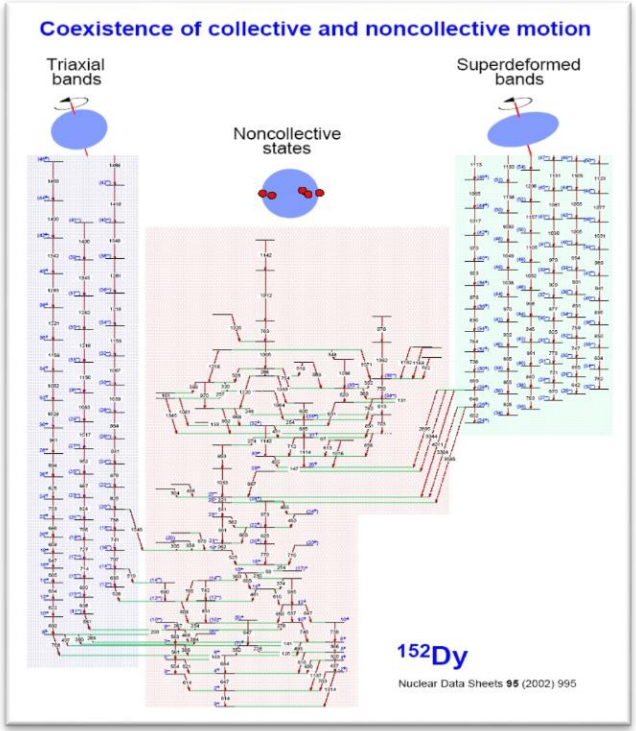
3,350 nuclei produced and studied

Discrete Quantized States

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

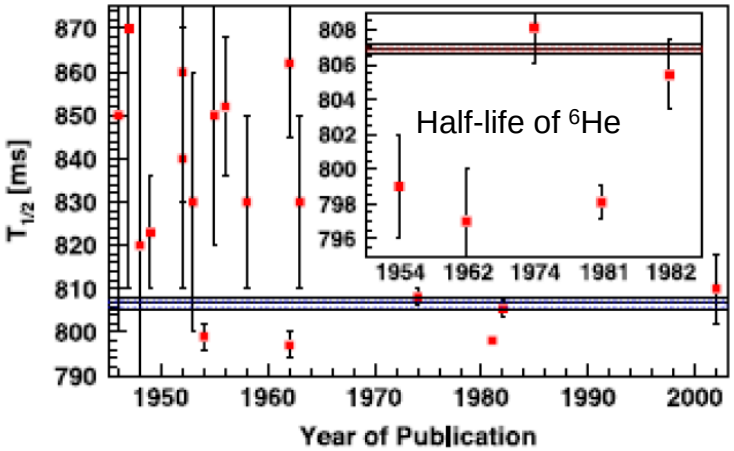
Emitted Radiation

- Energy
- Intensity
- Dipole, Quadrupole, …
- …



100+ years of experimental nuclear structure measurements

Arbiter of the "Truth"



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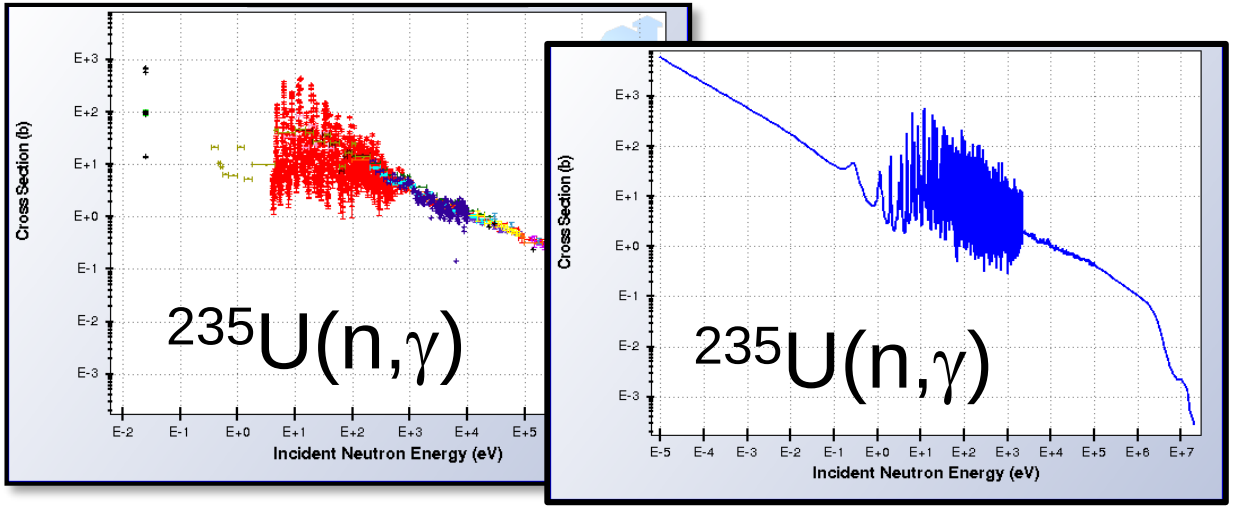
Nuclear Reactions Database (ENDF)

Cross section: related to the size of a nucleus

Probability of "hitting" the nucleus ~ πR^2

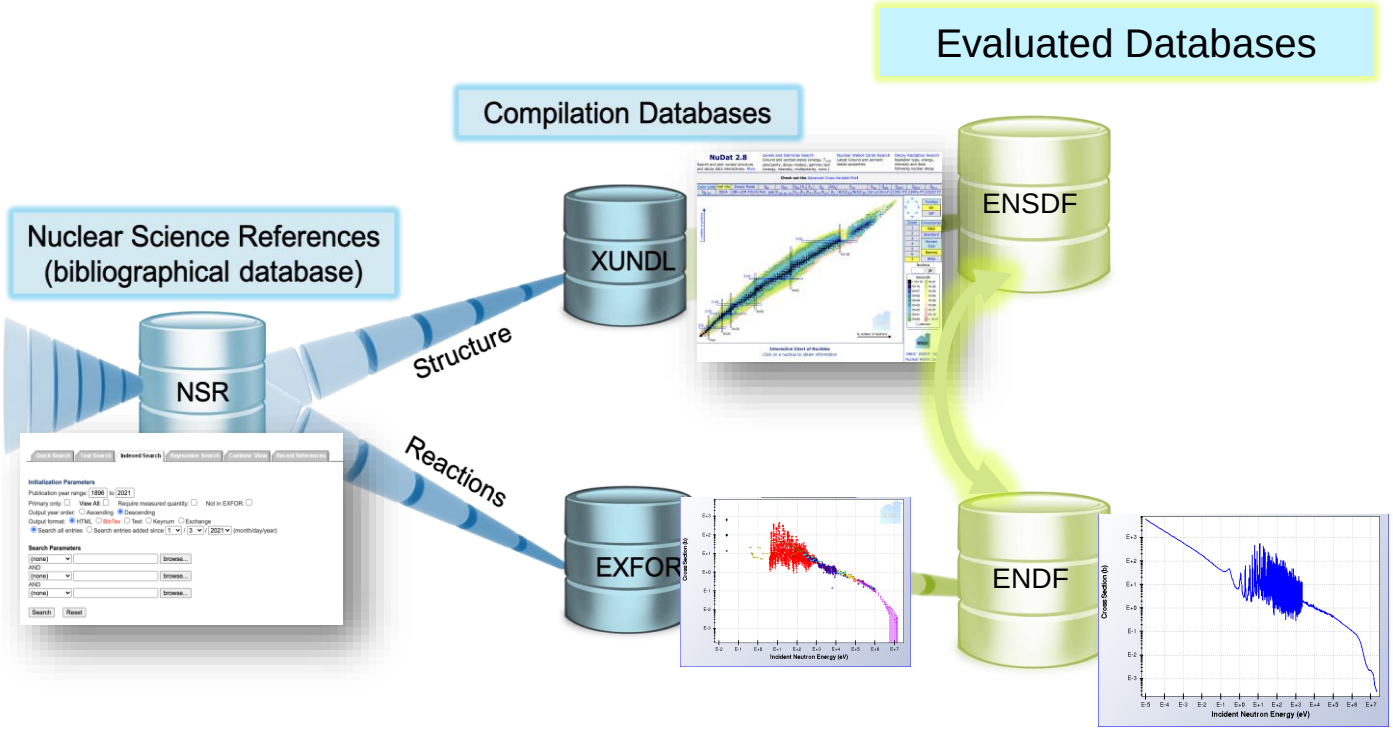
1 barn (b) = 10^{-24} cm^2

- Cross section as a function of incident particle energy
- Energy and angles of reaction products
- Neutron resonance parameters
- Neutron multiplicities
- Fission yields
- ….



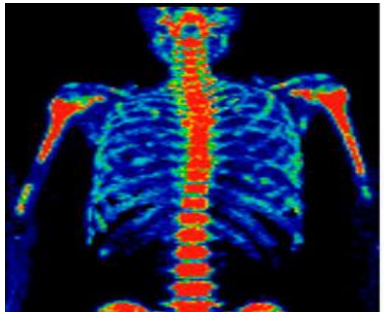
- Not all reactions and all energies can be measured
- Application of physics-based models to describe experimental data

Data Dissemination



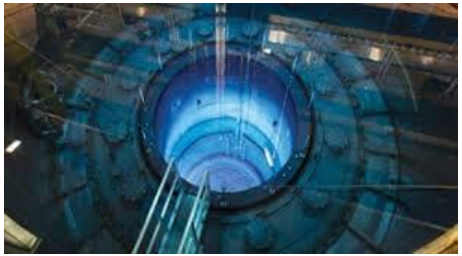
- Each database has web application to query and (plot) data
- Additional web applications for subsets of data

Applications of Nuclear Data



Nuclear Medicine

How can I produce and use radioactive isotopes in the body?



Nuclear Power

Is there new physics beyond the standard model and can we make the world safer?

Stockpile Stewardship

How do you ensure something will work after decades on the shelf?

Homeland Security

Space Exploration

How do I determine what's in something I can't see or touch?

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Nuclear Medicine

What can we use radioisotopes for in medicine?

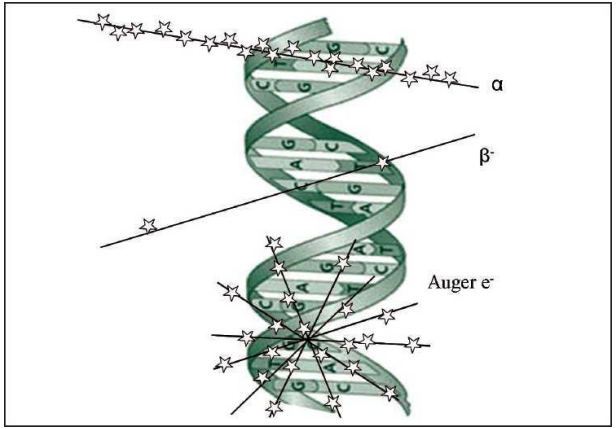
Imaging

X-rays, gamma rays

Therapy

Alphas, betas, Auger electrons

Targeted Radionuclide Therapy



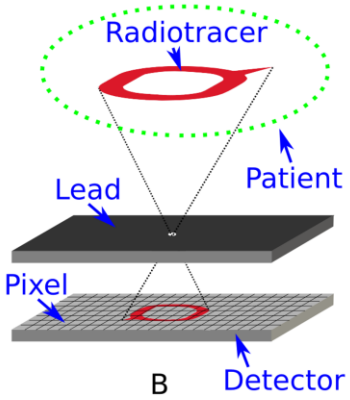
M. Sadeghi et al., J Can Res Ther 2010;6:239

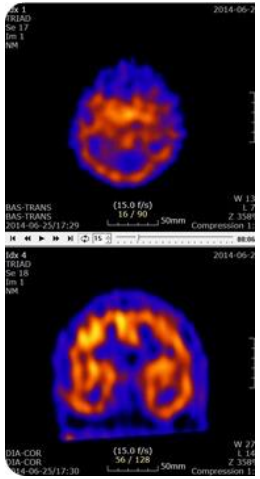
- Ionizing radiation to kill cancer cells and shrink tumors
- Uses molecule labeled with radionuclide

Diagnostic Imaging with Radioisotopes

SPECT

Single Photon Emission Tomography

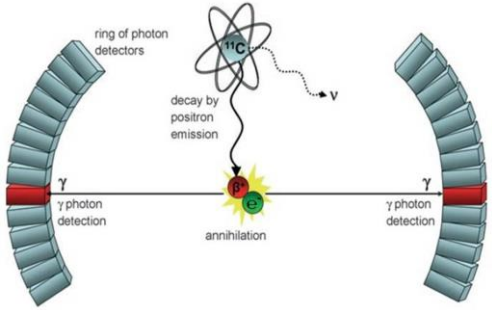


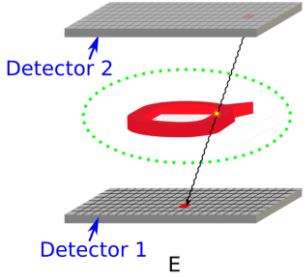


^{99m}Tc, ^{123}I, ^{121}I, ^{67}Ga, ^{201}Tl

PET

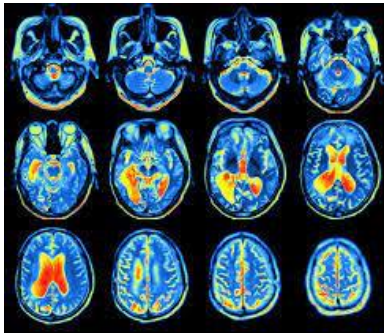
Positron Emission Tomography





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

^{18}F, ^{82}Rb, ^{13}N, ^{66}Ga



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As an example : ^{86}Y

IOP Publishing | Institute of Physics and Engineering in Medicine
Physics in Medicine & Biology
Phys. Med. Biol. 60 (2015) 3479–3497
doi:10.1088/0031-9155/60/9/3479

PET imaging with the non-pure positron emitters: ^{55}Co, ^{86}Y and ^{124}I

P E N Braad[1], S B Hansen[2], H Thisgaard[1] and

Eur J Nucl Med Mol Imaging (2016) 43:925–937
DOI 10.1007/s00259-015-3254-8

ORIGINAL ARTICLE

PHYSICAL REVIEW C VOLUME 2, NUMBER 6 DECEMBER 1970

Energy Levels in ^{86}Sr from the Decay of 14.6-h ^{86}Y

A. V. Ramayya, B. Van Nooijen,* J. W. Ford, D. Krmpotić,† and J. H. Hamilton
Physics Department,‡ Vanderbilt University, Nashville, Tennessee 37203

and

J. J. Pinajian and Noah R. Johnson
Oak Ridge National Laboratory,§ Oak Ridge, Tennessee 37803
(Received 20 April 1970)

ELSEVIER journal homepage: www.elsevier.com/locate/apradiso

Tailoring medium energy proton beam to induce low energy nuclear reactions in $^{86}SrCl_2$ for production of PET radioisotope ^{86}Y☆

Dmitri G. Medvedev*, Leonard F. Mausner, Philip Pile

CrossMark

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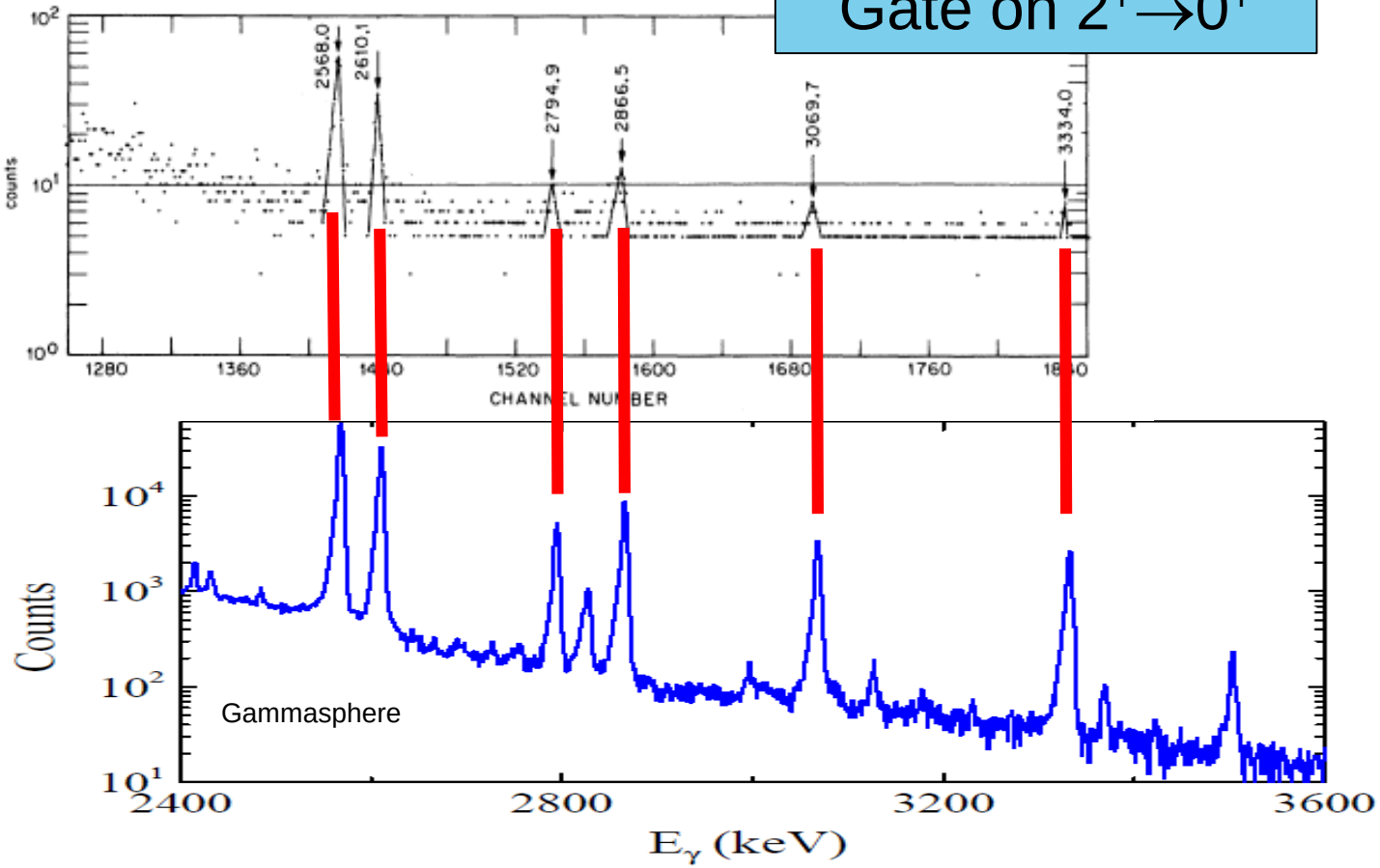
National La

Results on ^{86}Y

Gate on $2^+ \rightarrow 0^+$



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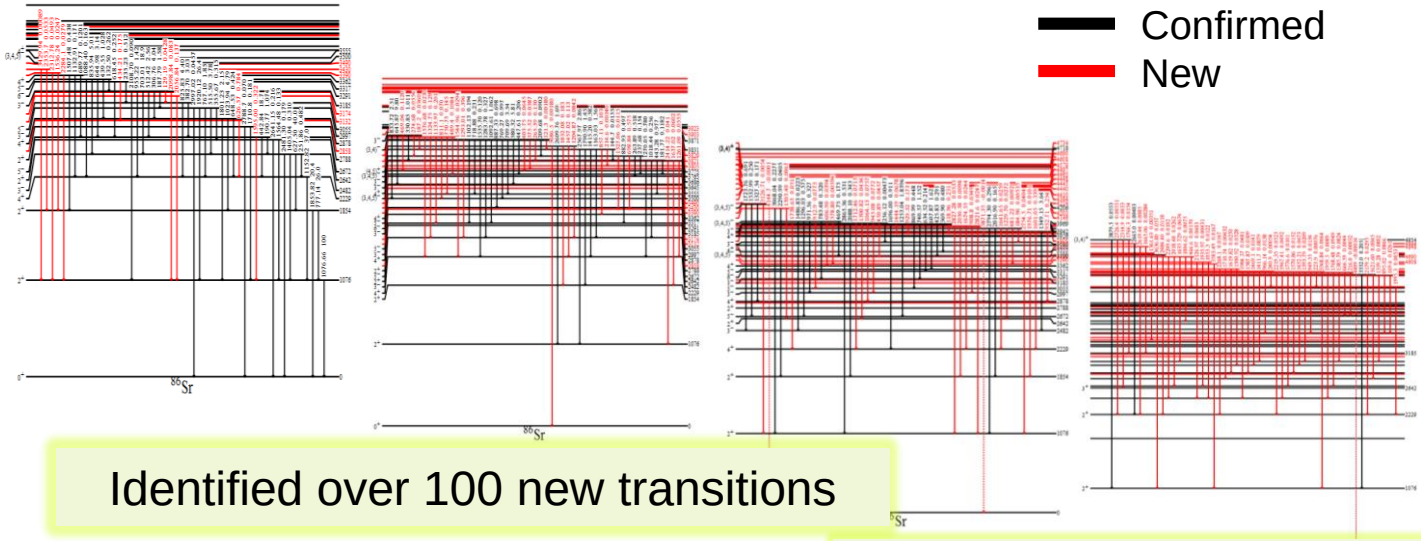
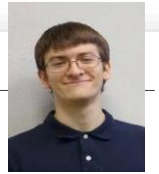
Revised Decay Scheme for ^{86}Y



Identified over 100 new transitions

511-keV intensity decreases by 15% !

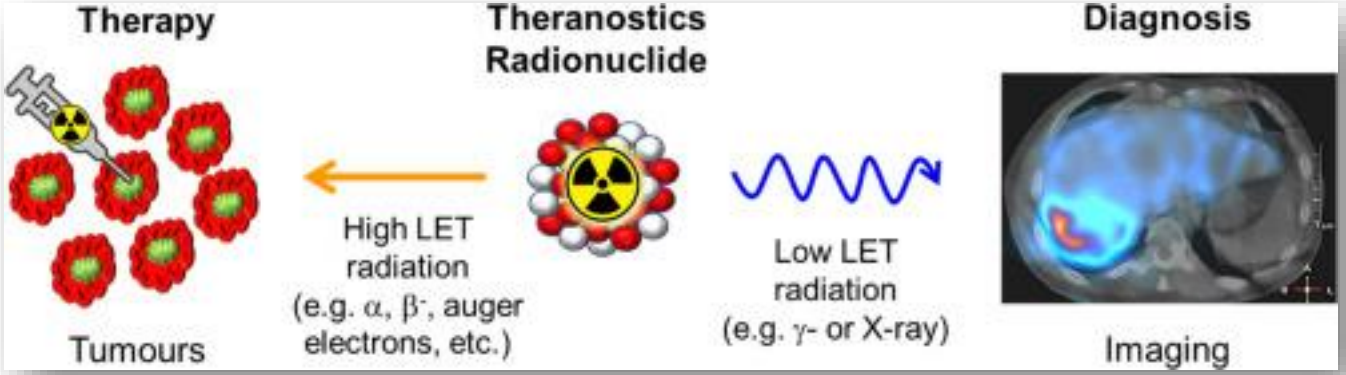


PHYSICAL REVIEW C **102**, 034316 (2020)

State-of-the-art γ-ray assay of ^{86}Y for medical imaging

A. C. Gula,[1,2] E. A. McCutchan,[2] C. J. Lister,[3] J. P. Greene,[4] S. Zhu,[2,4] P. A. Ellison,[5] R. J. Nickles,[5] M. P. Carpenter,[4] Suzanne V. Smith,[6] and A. A. Sonzogni[2]

The Future : Theranostics



H.Y. Tan *et al*., Nucl. Med. Biology **90**, 55 (2020).


www.nature.com/scientificreports

scientific reports

Check for updates

OPEN **High yield cyclotron production of a novel $^{133/135}$La theranostic pair for nuclear medicine**

Bryce J. B. Nelson[1], John Wilson[1], Jan D. Andersson[1,2] & Frank Wuest[1]

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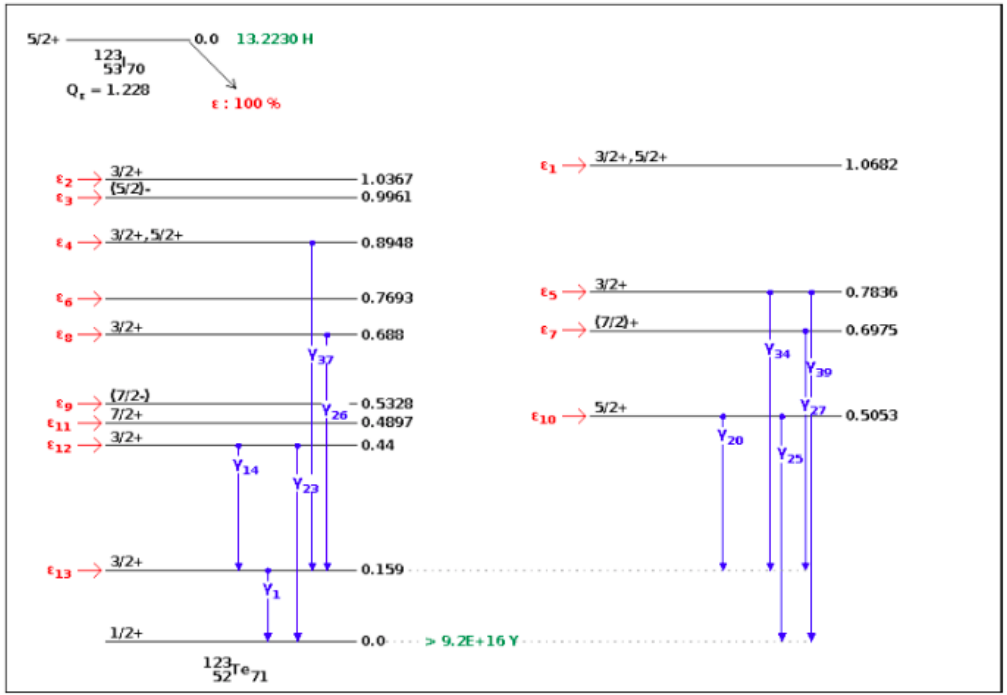
MIRD – yes we have an app for that !
Medical Internal Radiation Dosimetry



53-IODINE-123
Half-life = 13.2230 Hours
Decay modes: ε
References:
123I EC DECAY (13.2230 H)

Download as .csv

Radiations	γ(i) (Bq-s)$^{-1}$	E(i) (MeV)	γ(i)×E(i)
γ_1	8.36×10^{-1}	1.589×10^{-1}	1.32×10^{-1}
ce-K, γ_1	1.34×10^{-1}	1.271×10^{-1}	1.71×10^{-2}
ce-L, γ_1	1.74×10^{-2}	1.540×10^{-1}[a]	2.69×10^{-3}
ce-M, γ_1	3.48×10^{-3}	1.579×10^{-1}[a]	5.50×10^{-4}
γ_{14}	7.19×10^{-4}	2.810×10^{-1}	2.02×10^{-4}
γ_{20}	1.20×10^{-3}	3.463×10^{-1}	4.15×10^{-4}
γ_{23}	3.88×10^{-3}	4.400×10^{-1}	1.70×10^{-3}
γ_{25}	2.88×10^{-3}	5.053×10^{-1}	1.45×10^{-3}
γ_{26}	1.27×10^{-2}	5.289×10^{-1}	6.71×10^{-3}
γ_{27}	3.10×10^{-3}	5.385×10^{-1}	1.66×10^{-3}
γ_{34}	7.80×10^{-4}	6.245×10^{-1}	4.87×10^{-4}
γ_{37}	4.70×10^{-4}	7.358×10^{-1}	3.45×10^{-4}
γ_{39}	5.30×10^{-4}	7.835×10^{-1}	4.15×10^{-4}
L X-ray	8.96×10^{-2}	3.770×10^{-3}*	3.37×10^{-4}
Kα2 X-ray	2.47×10^{-1}	2.720×10^{-2}	6.71×10^{-3}
Kα1 X-ray	4.56×10^{-1}	2.747×10^{-2}	1.25×10^{-2}
Kβ3 X-ray	4.20×10^{-2}	3.094×10^{-2}*	1.30×10^{-3}

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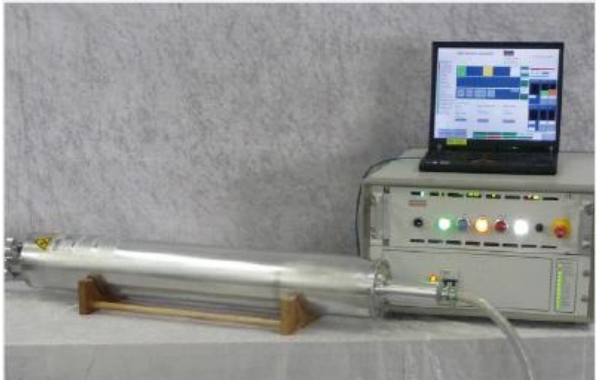
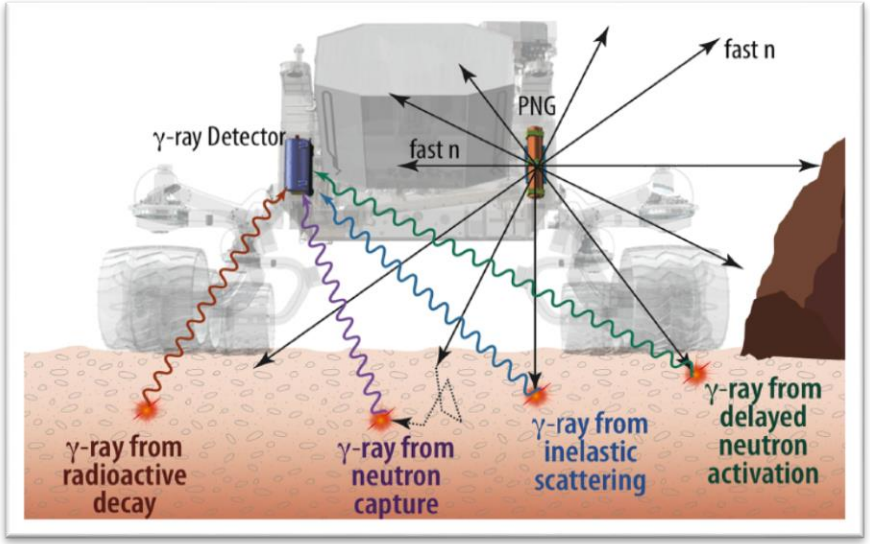
Active Interrogation with Neutrons



Compact DT neutron generators

Use our Q-value calculator tool to find Q values for D+T and reaction products. What energy of neutrons are produced?

What reactions happen when one shoots MeV-ish neutrons at something?



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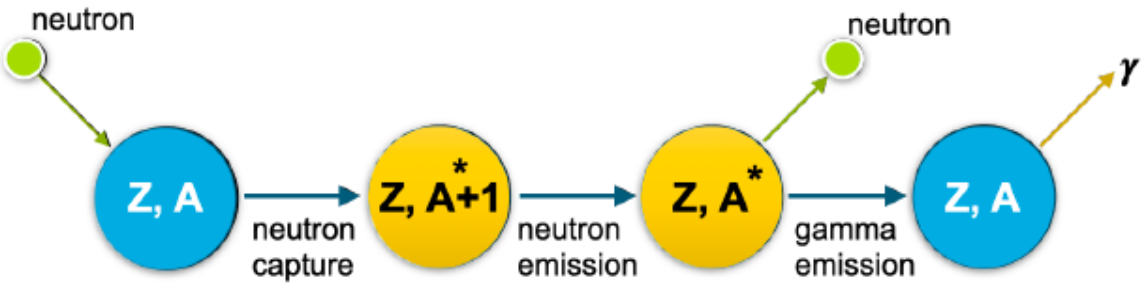
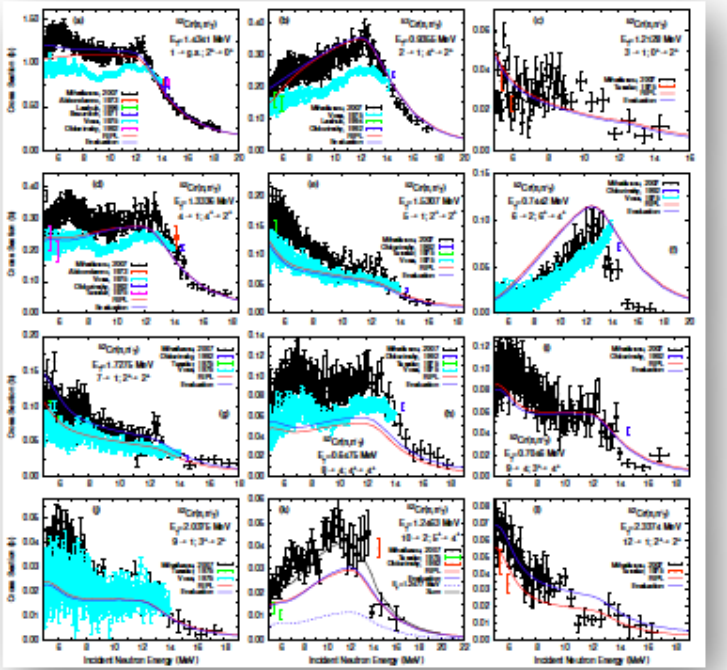
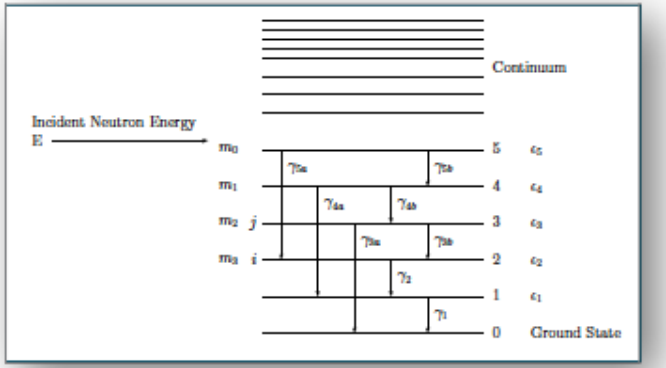
Nowicki, S. F., et al, (2017), Modeled Martian subsurface elemental composition measurements with the Probing In situ with Neutron and Gamma ray instrument, Earth and Space Science, 4, 76– 90, doi:10.1002/2016EA000162.

Inelastic reaction gammas





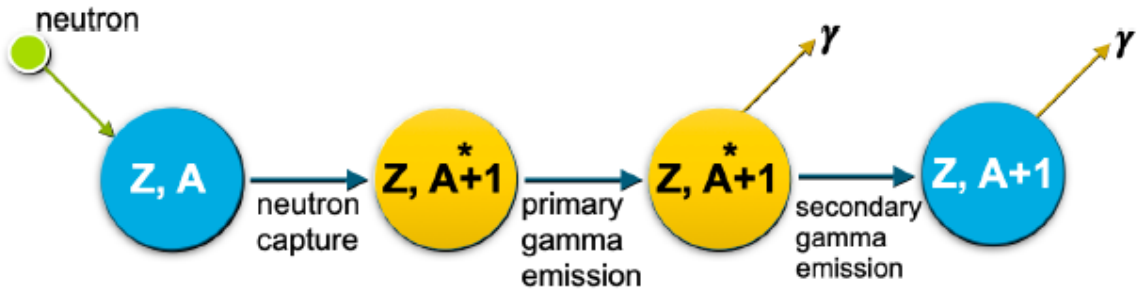
G. Nobre et al., Nucl. Data Sheets 173: 1-41 (2021)

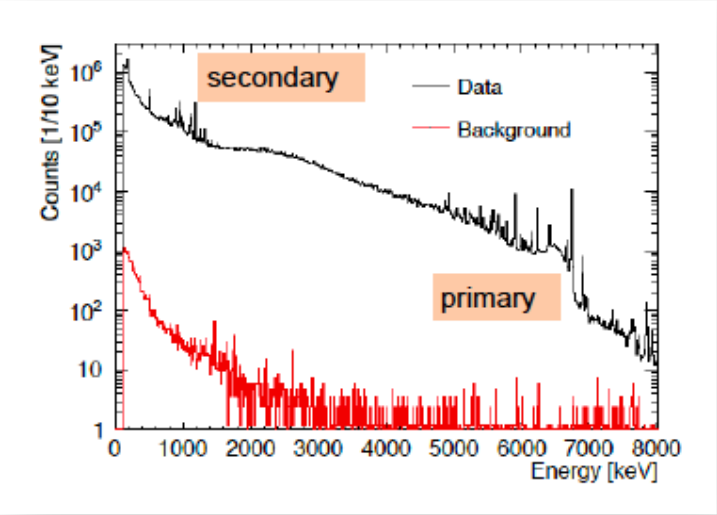


Decay from inelastic state is

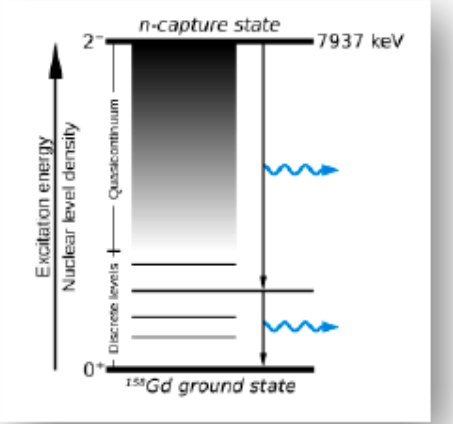
- Initially populated by compound reaction
- Cascade lower energy gammas
- Provides a unique fingerprint for each isotope

Thermal neutron capture gammas





K. Hagiwara et al., Prog Theor. Exp. Phys. 0000, 2015



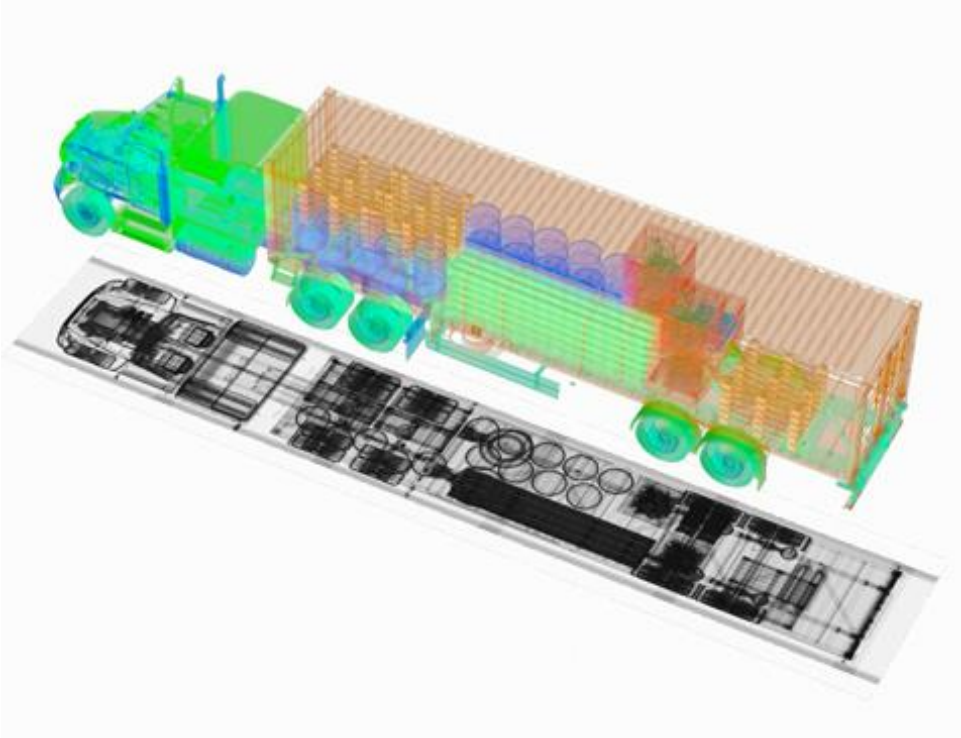
Decay from capture state is
- First high energy gammas - primary
- Followed by lower energy gammas –secondary
- Provides a unique fingerprint for each isotope

What’s in the box?

Use a combination of

- Traditional x-rays
- Active neutron interrogation
- NRF

Complete characterization in few minutes

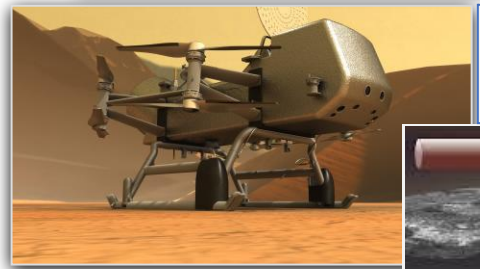


https://passportsystems.com

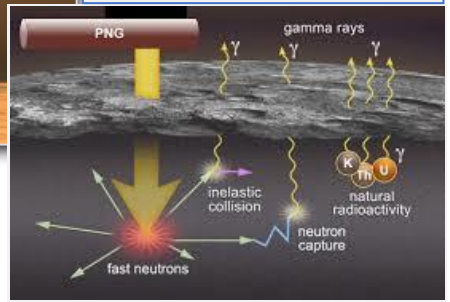
Some additional applications

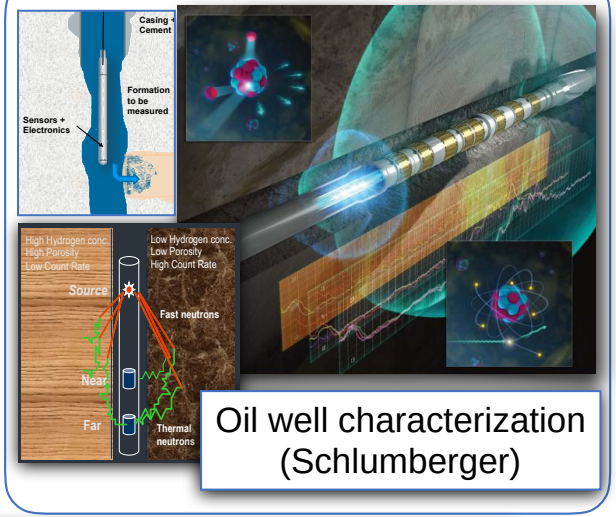
** Images taken from www.nasa.gov, and from Unzueta's, and Mauborgne's talks in WANDA 2020*

Dragonfly mission to Saturn's moon Titan



- **Gamma-ray detection system**
  - Thermal neutron capture (TNC)
  - Inelastic Scattering (INS)

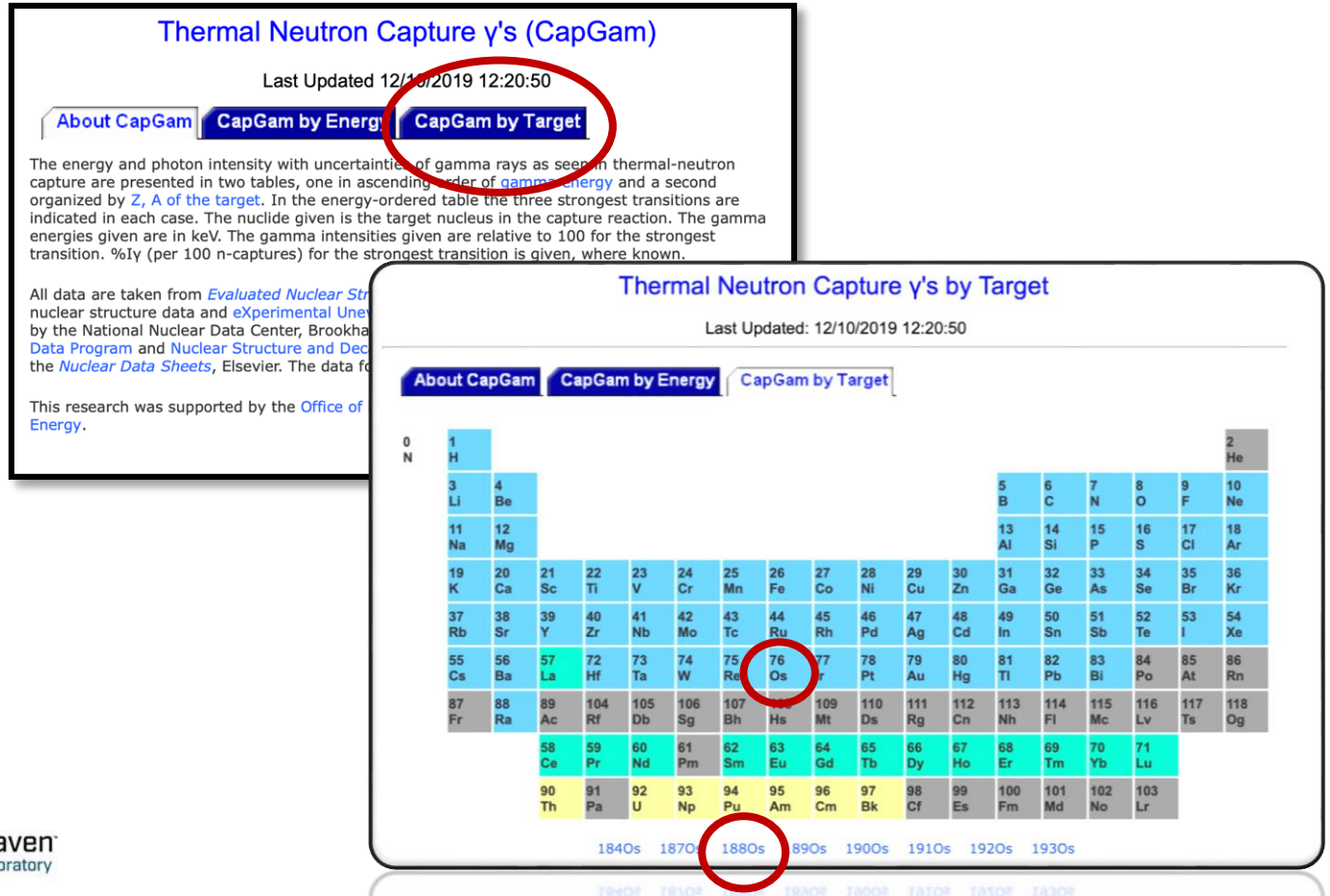




Oil well characterization (Schlumberger)

- Characterization of materials rely on measuring neutron-induced gammas
- These depend on:
  - Precise and thorough experimental knowledge
  - Incorporation of data into evaluated files
  - Proper handling through transport codes, so that information is not lost

CapGam Web Application –



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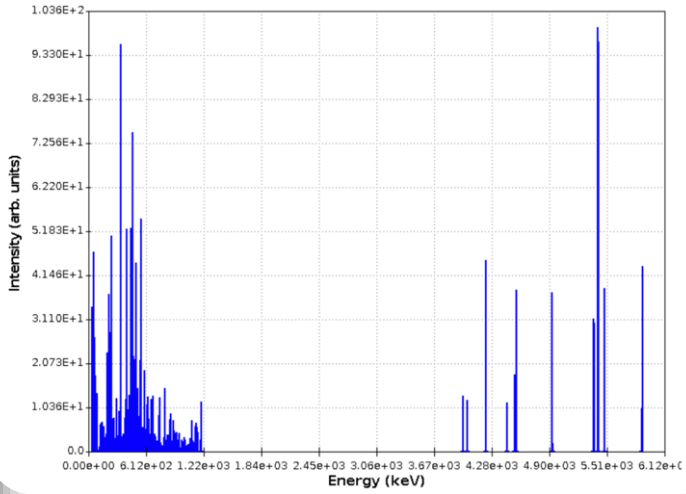
CapGam Web Application

Tabular data and option to download numerical values

New feature:
Histogram of intensity vs. energy

Download as .csv

E(γ) (keV)	ΔE(γ) (keV)	I(γ)/I(γ)max (%)	Δ(I(γ)/I(γ)max)
36.14	*0.04*	33.762	*7.51*
59.08	*0.03*	46.945	*10.43*
64.96	*0.07*	4.18	*1.3*
66.55	*0.04*	26.688	*6.01*
69.55	*0.06*	20.9	*5.83*
95.27	*0.04*	13.505	*2.98*
118.50	*0.09*	0.997	*0.31*
122.47	*0.07*	0.932	*0.23*
124.25	*0.06*	1.0611	*0.26*
129.42	*0.04*	6.141	*1.38*
132.16	*0.05*	2.958	*0.7*
138.30	*0.04*	6.463	*1.43*
147.12	*0.04*	6.817	*1.51*
149.86	*0.04*	5.498	*1.23*
162.74	*0.09*	1.0289	*0.34*
164.03	*0.04*	5.723	*1.28*
175.62	*0.07*	3.0868	*0.79*
181.06	*0.06*	2.605	*0.63*



Transforming our vast body of data into something unexpected

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What applications come to mind when you think of a nuclear reactor?

- Power
- Decay heat
- Medical isotope production
- Neutrino Oscillations
- Non proliferation

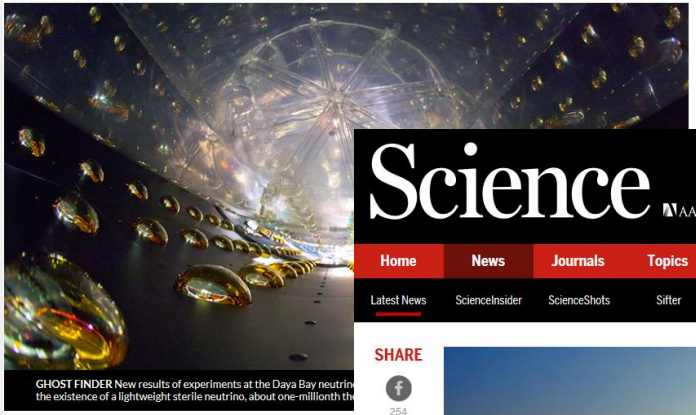
Antineutrinos from a reactor are a really hot topic

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
the existence of a lightweight sterile neutrino, about one-millionth th

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3

The Daya Bay Reactor Neutrino Experiment studies antineutrinos from six reactors near Shenzhen, China.
Photo courtesy of Lawrence Berkeley National Laboratory/Roy Kaltschmidt © 2010 The Regents of the University of California, through the Lawrence Berkeley National Laborator

Weird sterile neutrinos may not exist, suggest new data from nuclear reactors

By Adrian Cho | Apr. 6, 2017 , 5:30 PM

University of California - Lawrence Berkeley National Laboratory

Sterile neutrino search hits roadblock at reactors

05/04/17 | By Kathryn Jepsen

A new result from the Daya Bay collaboration reveals both limitations and strengths of experiments studying antineutrinos at nuclear reactors.

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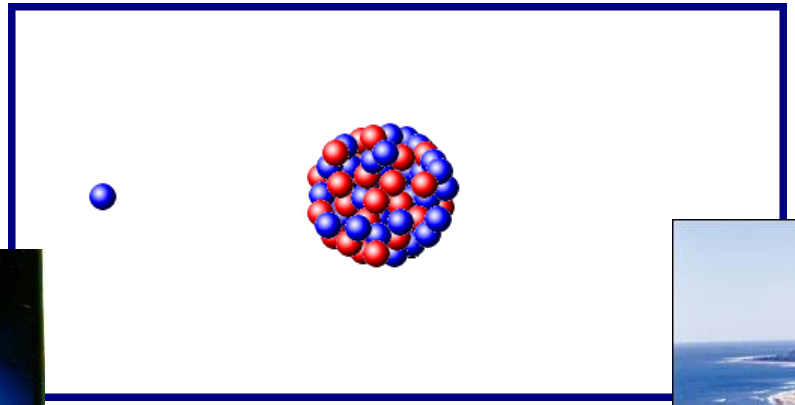
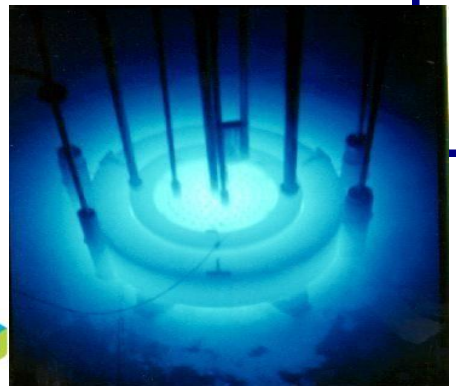
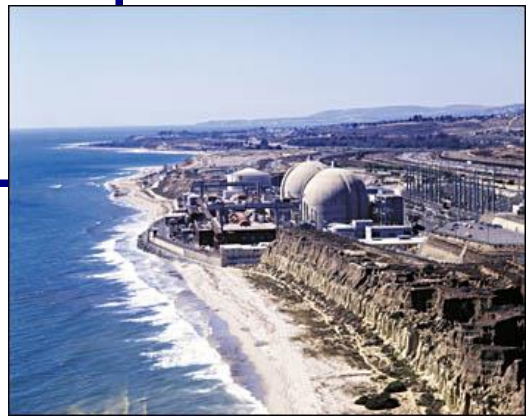
Nuclear Physics Powering a Reactor

- 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



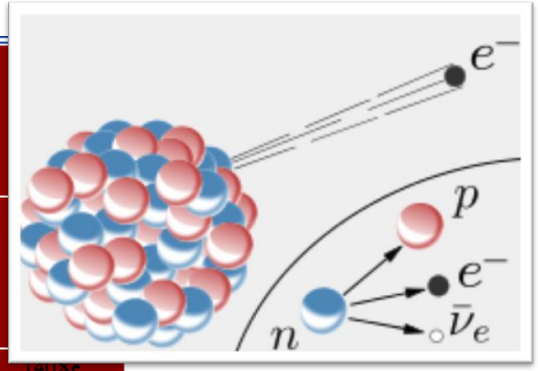




Yields of Fission Fragments

Z, number of protons

136Ba STABLE 7.854% 2.4E-8	137Ba STABLE 11.232% 1.3E-6	138Ba STABLE 71.698% 4.E-5	139Ba 83.06 M β-: 100.00% 7.E-4	140Ba 12.7527 D β-: 100.00% 0.0049	141Ba 18.27 M β-: 100.00% 0.0166	
135Cs 2.3E+6 Y β-: 100.00% 2.5E-6	136Cs 13.04 D β-: 100.00% 2.8E-5	137Cs [illegible].08 Y β-: 10[illegible].00% 6.0E-4	138Cs 33.41 M β-: 100.00% 0.00223	139Cs 9.27 M β-: 100.00% 0.0131	140Cs 63.7 S β-: 100.00% 0.0207	
134Xe >5.8E+22 Y 10.4357% 2β- 2.5E-4	135Xe 9.14 H β-: 100.00% 0.00178	136Xe >2.4E+21 Y 8.8573% 2β- 0.022	137Xe [illegible]18 M β-: 1[illegible].00% 0.0319	138Xe 14.08 M β-: 100.00% 0.0481	139Xe 39.68 S β-: 100.00% 0.0432	140Xe 13.60 S β-: 100.00% 0.0351
133I 20.83 H β-: 100.00% 8.E-4	134I 52.5 M β-: 100.00% 0.0036	135I 6.58 H β-: 100.00% 0.0293	136I 83.4 S β-: 100.00% 0.0125	137I 24.5 S β-: 100.00% β-n: 7.14% 0.0262	138I 6.23 S β-: 100.00% β-n: 5.56% 0.0142	139I 2.280 S β-: 100.00% β-n: 10.00% 0.0077
132Te 3.204 D β-: 100.00% 0.0153	133Te 12.5 M β-: 100.00% 0.0299	134Te 41.8 M β-: 100.00% 0.0622	135Te 19.0 S β-: 100.00% 0.0322	136Te 17.63 S β-: 100.00% β-n: 1.31% 0.0132	137Te 2.49 S β-: 100.00% β-n: 2.99% 0.0039	138Te 1.4 S β-: 100.00% β-n: 6.30% 7.E-4



Flux ~ 10^{20} antineutrinos / s

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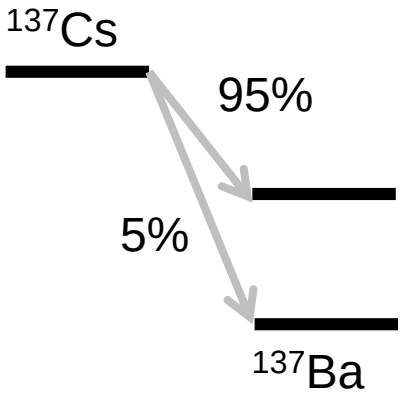
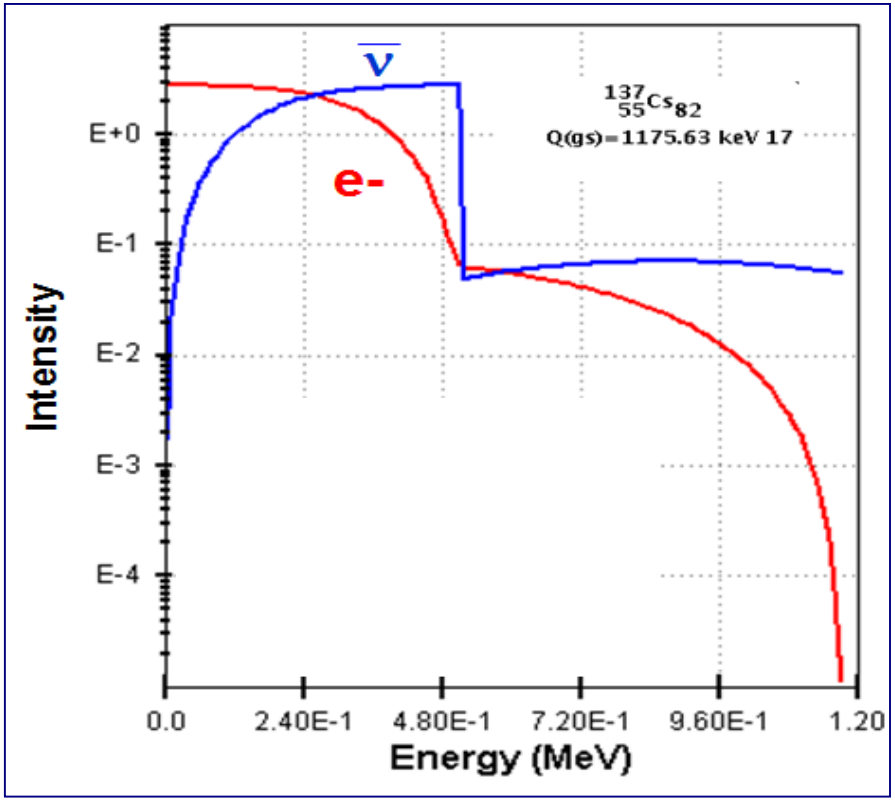
Simple Example : ^{137}Cs





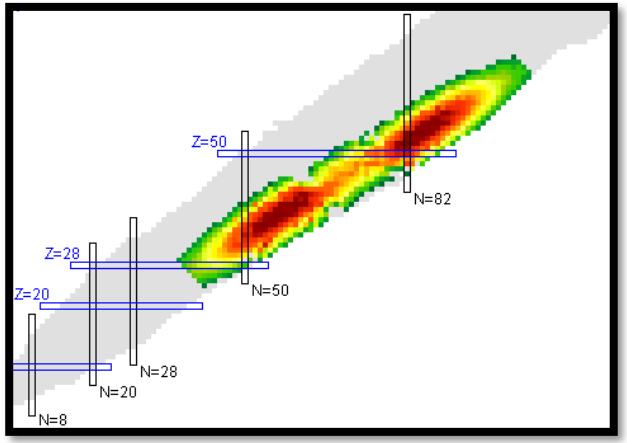
$$S(E)=N\,W\,(W^2-1)^{1/2}(W-W_0)^2\,F(Z,W)\,C(Z,W)(1+\delta)$$

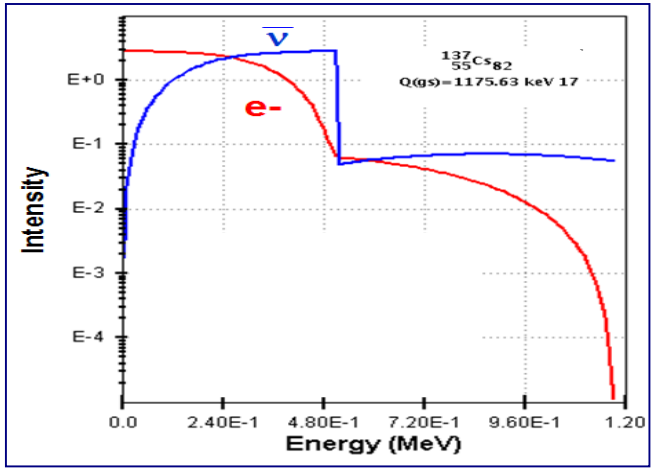
The Summation Method

$$S(E) = \sum CFY_i S_i(E)$$

Cumulative Fission Yields

Individual Spectra

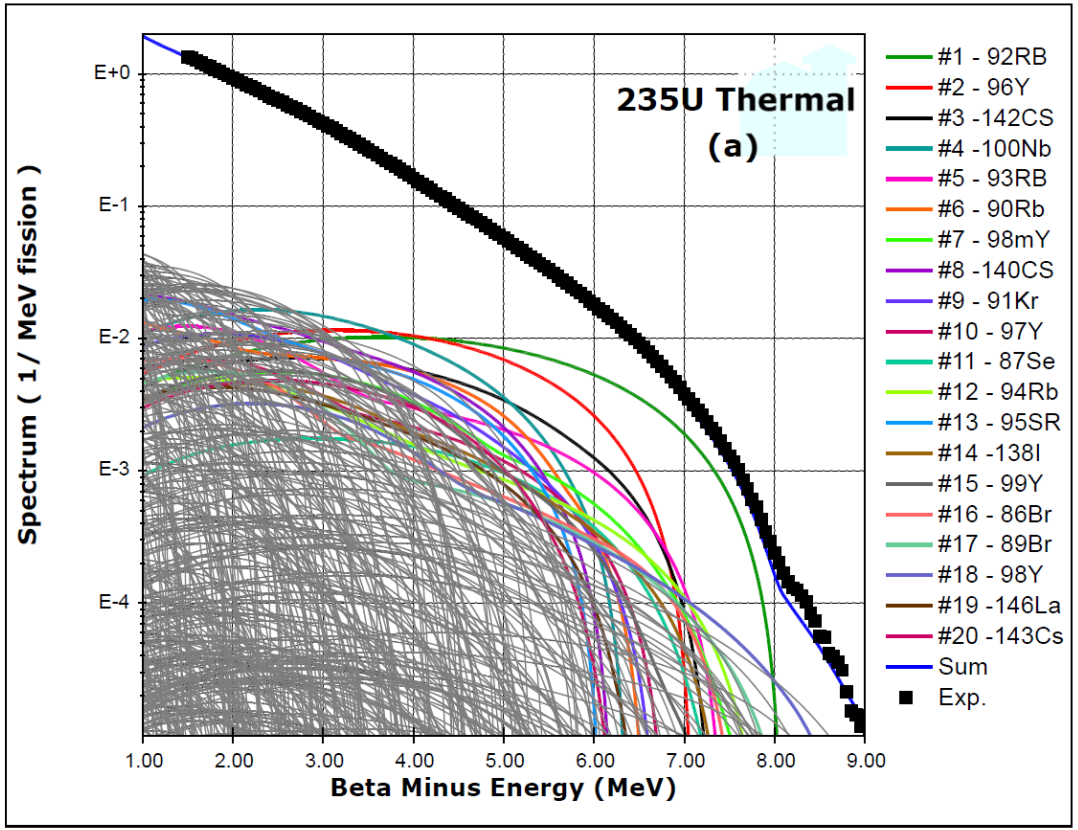




Low precision (~10 % uncertainty) but …

- Can calculate for any fissioning isotope
- Has direct link to underlying physics
- Doesn't rely on a single measurement

Summation Calculations for ^{235}U



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A.A. Sonzogni, T.D. Johnson, E.A. McCutchan, Phys. Rev. C 91, 011301(R) (2015).

The ghost particle

Antineutrinos are produced in beta decay

$$n \rightarrow p + e^{-} + \bar{\nu}$$

How do you measure something
with no electrical charge interacting
only through weak interaction?

Bethe-Peierls (1934) – detection through **inverse beta decay**

$$\bar{\nu} + p \rightarrow n + e^{+}$$

The problem: cross section for reaction is ~10^{-44} cm^2 !!!
That's 10^{-20} barns !!!

The chances of a neutrino actually hitting something as it travels through all this howling emptiness are roughly comparable to that of dropping a ball bearing at random from a cruising 747 and hitting, say, an egg sandwich"

Average distance traveled in lead brick

1 light year

-- Hitchhiker's Guide to the Galaxy

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Ghostbusting with Probability

How to detect the ghost particle ?

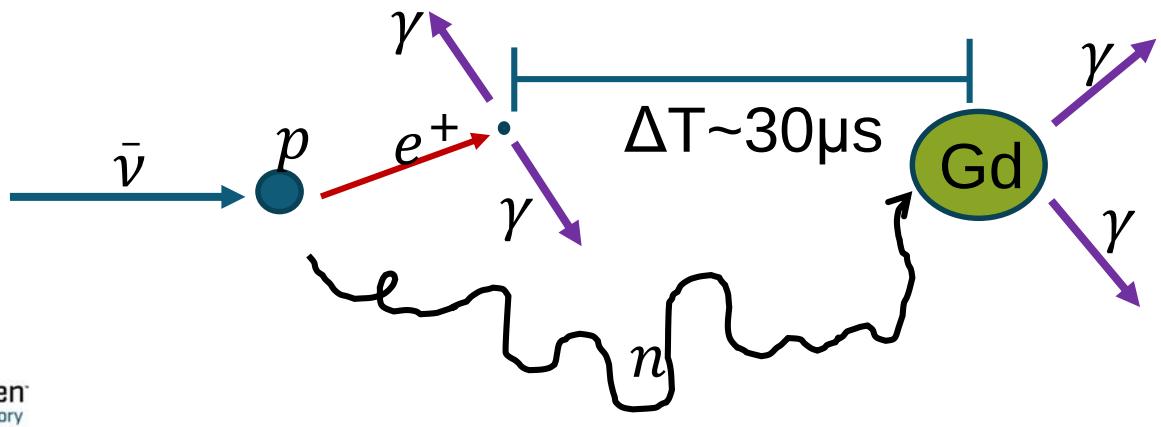
Intense source of neutrinos

×

Really big detector

And some nuclear physics !

$$\bar{\nu} + p \rightarrow n + e^{+}$$



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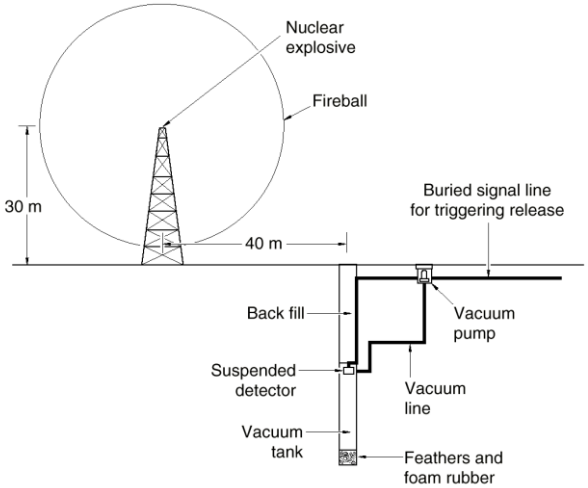
The Neutrino Discovery (1953)

Cowan and Reines:

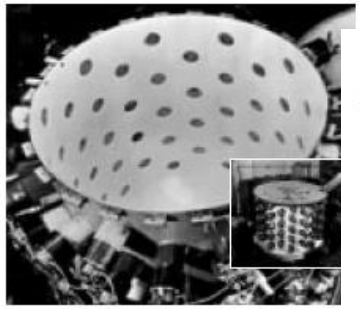
1995 Nobel Prize for detection of the neutrino

A saner approach :
Nuclear Reactor

Outside the Box thinking

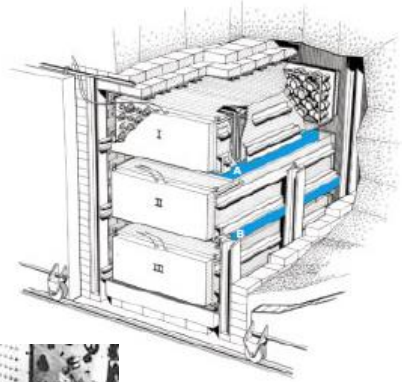


Approved at Los Alamos



The Hanford Neutrino Detector

Savannah River

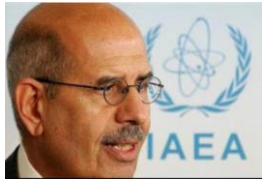


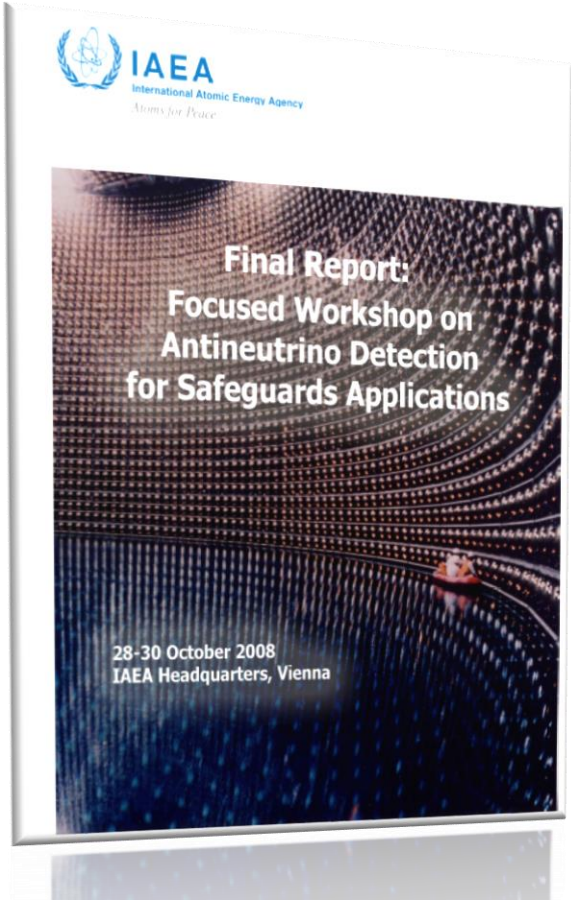
Fred Reines Clyde Cowan

Brookhaven National Laboratory

More outside-the-box thinking

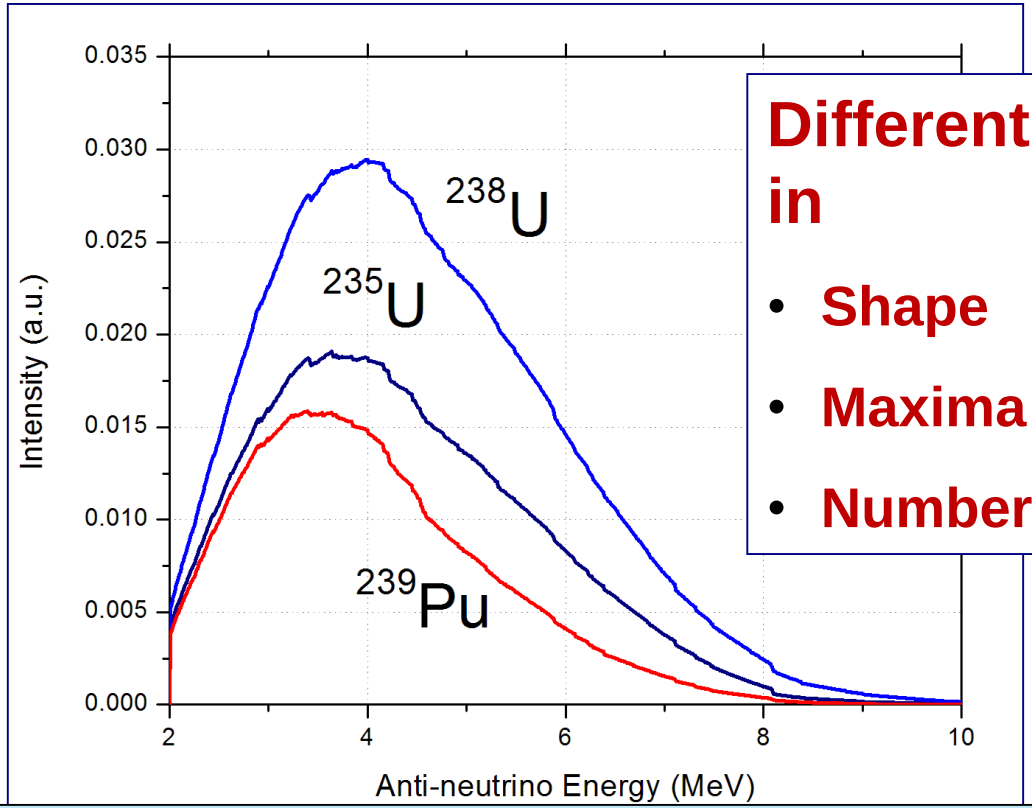
"In regard to nuclear proliferation and arms control, the fundamental problem is clear: Either we begin finding creative, outside-the-box
solutions or the international nuclear safeguards regime will become obsolete."
-
M. ElBaradei,
then Director General of the IAEA
Washington Post, June 14, 2006





- 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

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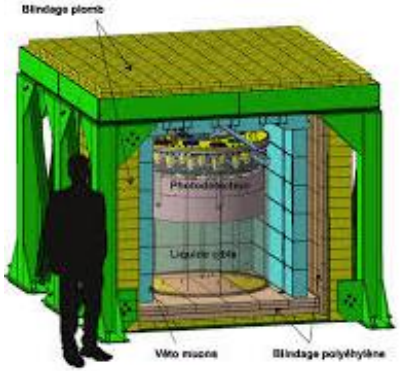
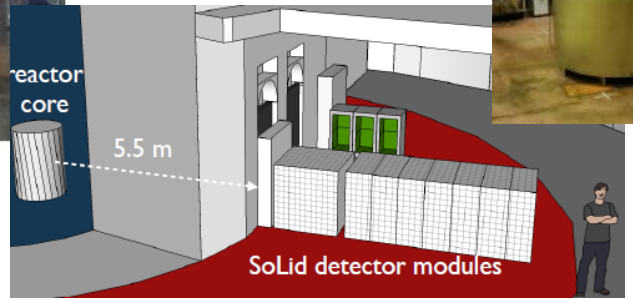
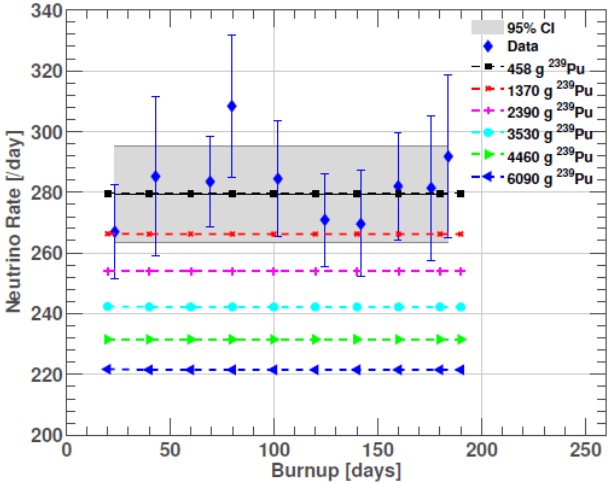
Active and exciting developments worldwide







Many efforts

- USA
- Canada
- Japan
- France
- Brazil
- Italy
- UK
- Korea

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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

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Want more fun facts about nuclei?

National Nuclear Data Center @NNDC_BNL · Feb 14

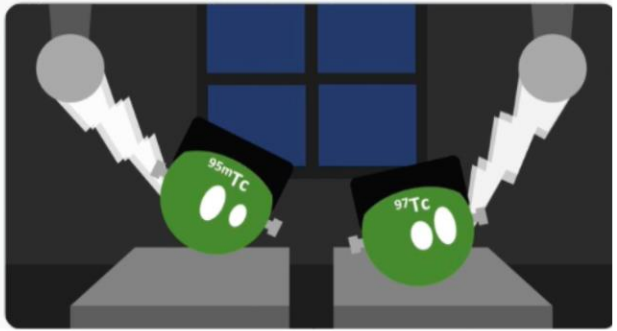
Tritium (3-Hydrogen), combined with phosphor (a material that emits light when exposed to radiation), leads to radioluminescence. This glow can be used to illuminate the hands of sport watches. #NuclideSpotlight #ScienceValentines

Follow us on Twitter!!
@NNDC_BNL

National Nuclear Data Center @NNDC_BNL · Nov 12, 2021

#NuclideSpotlight
#History

95m- and 97-Technetium were discovered in 1937 during an investigation of irradiated cyclotron parts.
Neither isotope occurs naturally, which made this the first study of synthetic elements produced by human beings.

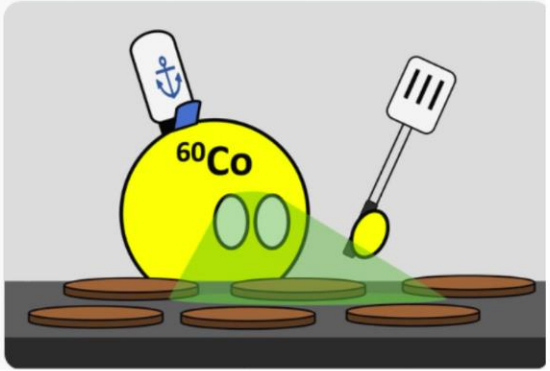


National Nuclear Data Center @NNDC_BNL · Oct 20, 2021

#NuclideSpotlight

Gamma rays can be used to kill bacteria and extend the shelf-life of food products.

This process (called "food irradiation") commonly uses 60-Cobalt, which:
- has a long half-life
- emits high-intensity gamma rays
- does not easily dissolve into water



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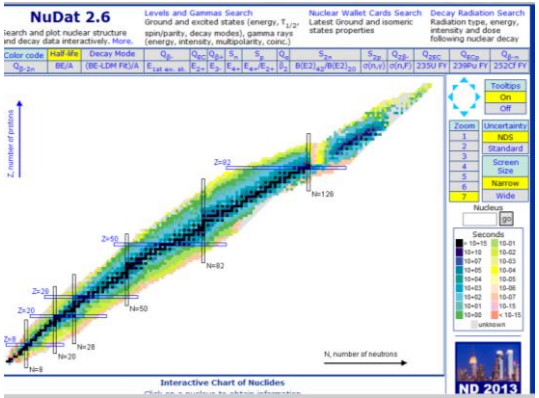
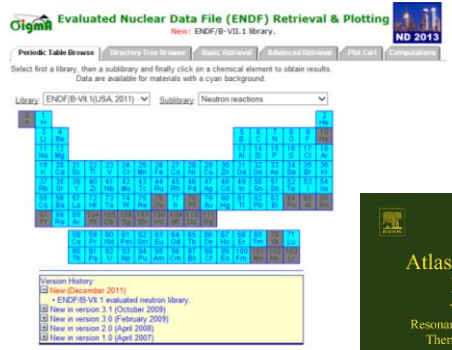
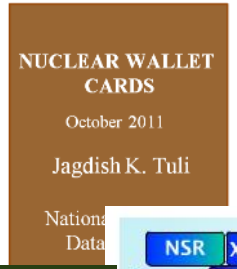
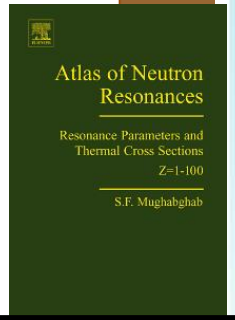
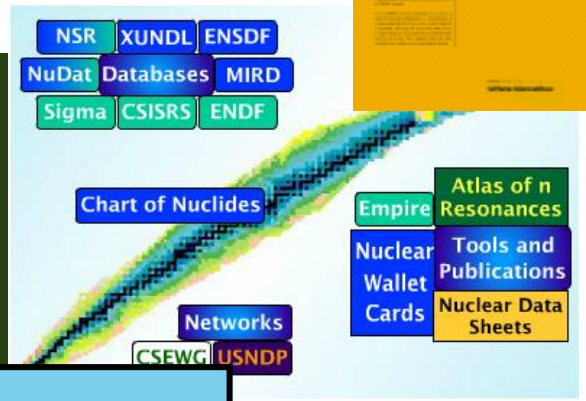
Take away message











Main thing to take away from this talk

- We work for YOU!!
- Comments/suggestions/criticisms are welcome
- You (should) shape the future of nuclear data