ORNL and physics

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Associate Laboratory Director
Physical Sciences Directorate

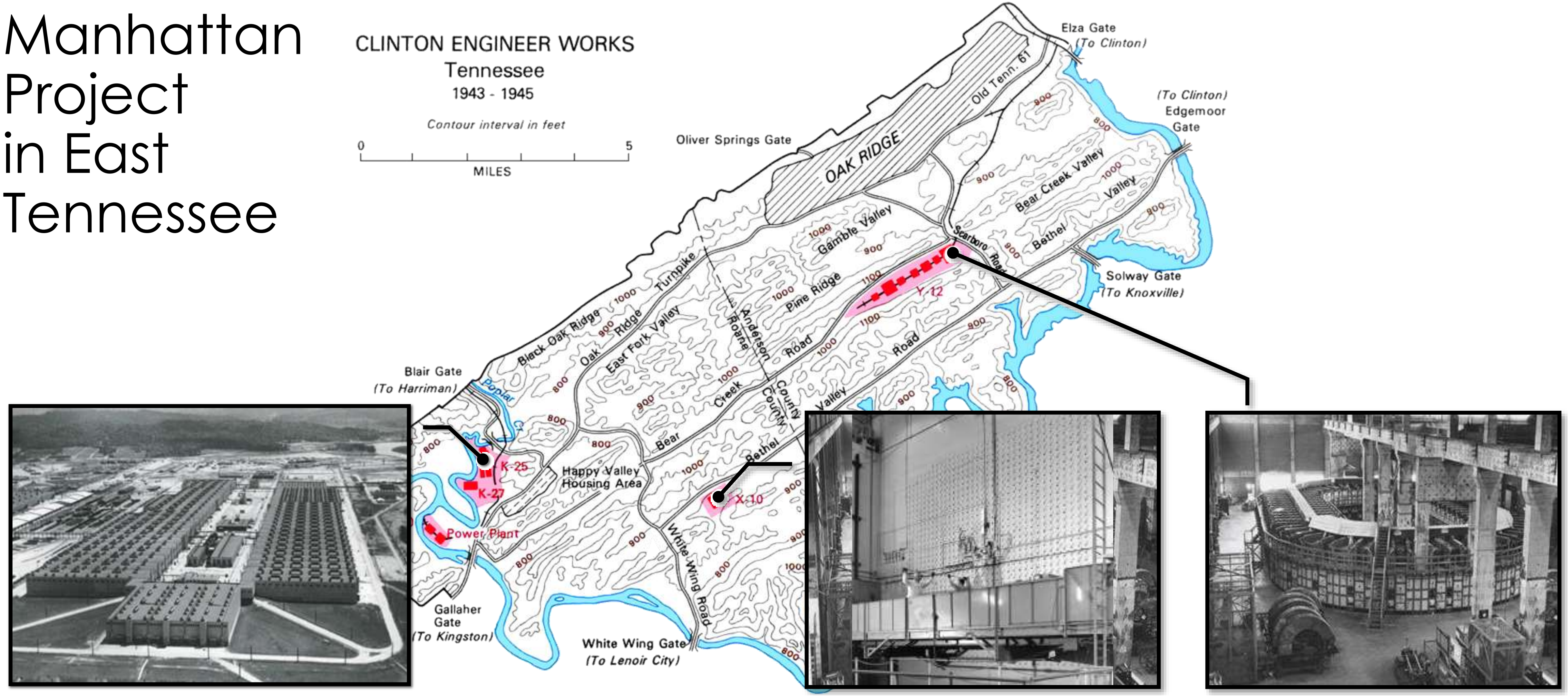
Exotic Beam Summer School
24 June 2019

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

Outline

- ORNL in brief
- Exciting physics
- Q&A

The Manhattan Project in East Tennessee



The Manhattan Project facilities evolved into the national laboratories

- Capitalize on the extraordinary scientific and technical capabilities assembled for the war effort
- Continue nuclear R&D with a focus on peaceful use
- Conduct unclassified fundamental research on a scale beyond the reach of a single university or industry

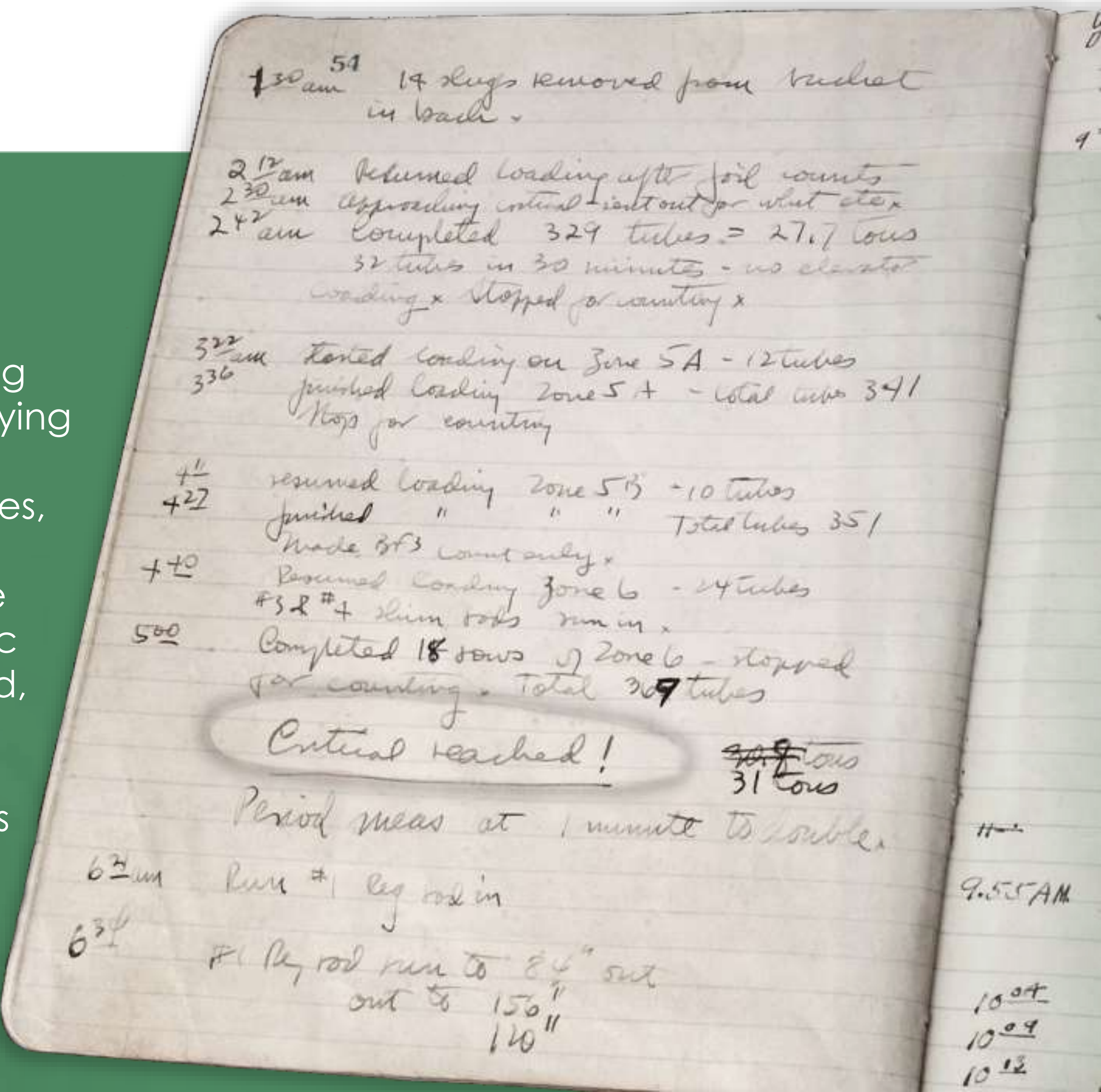
ATOMIC ENERGY COMMISSION • UNITED STATES OF AMERICA •

August 1, 1946: President Truman signs the Atomic Energy Act

ORNL's mission

Deliver scientific discoveries and technical breakthroughs needed to realize solutions in energy and national security and provide economic benefit to the nation

Integrating and applying 23 core capabilities, spanning the range from basic to applied, to deliver mission outcomes



54

1^{30} am 14 slugs removed from bucket in back.

2^{12} am Resumed loading after foil counts
2^{30} am Approaching critical sent out for what etc.
2^{42} am Completed 329 tubes = 27.7 tons
32 tubes in 30 minutes - no elevator loading. Stopped for counting.

3^{22} am Started loading on Zone 5A - 12 tubes
3^{36} finished loading Zone 5A - total tubes 341
Stops for counting

4^{11} resumed loading Zone 5B - 10 tubes
4^{27} finished " " " Total tubes 351
Made BF3 count only.
4^{40} Resumed loading Zone 6 - 24 tubes
#3 & #4 shim rods run in.
5^{00} Completed 18 rows of Zone 6 - stopped for counting. Total 369 tubes

Critical reached! ~~30.8~~ tons
31 tons

Period meas at 1 minute to double.

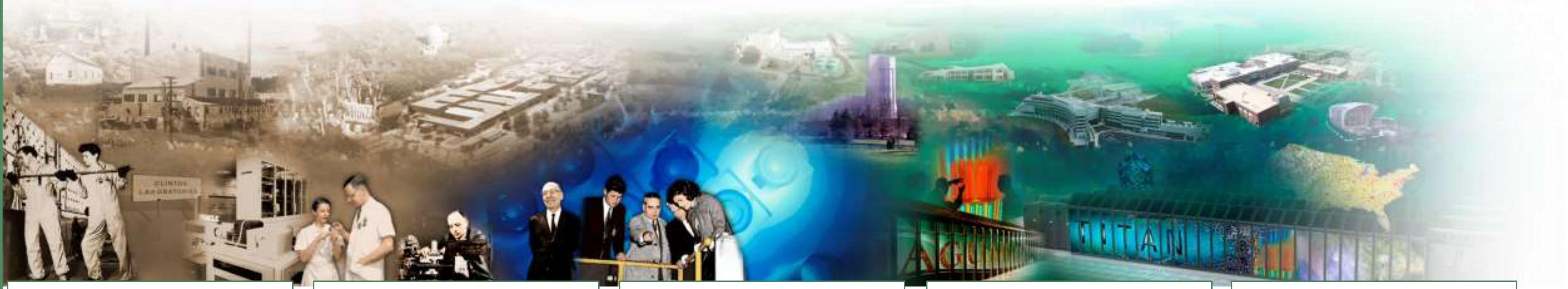
6^{24} am Run #1 reg rod in

6^{34} #1 Reg rod run to 84" out
out to 156"
120"

9.55 AM

10^{04}
10^{09}
10^{13}

ORNL has a distinguished history of making groundbreaking discoveries and meeting national needs



Development, production, and distribution of radioisotopes and stable isotopes

Science and engineering of the nuclear fuel cycle

Reactor technology

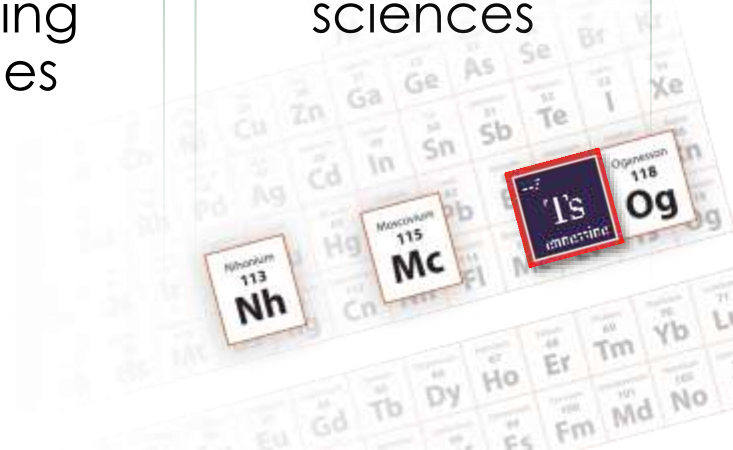
Materials and fuels

Separations chemistry

Development of neutron scattering, neutron activation analysis, and other innovative research tools

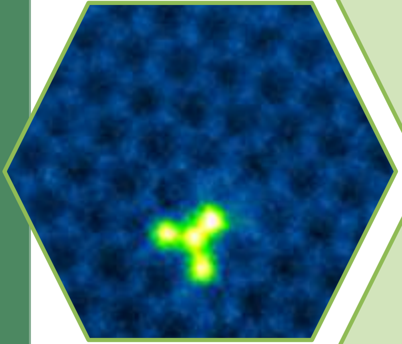
Development and application of high-performance computing resources

Delivering advances in physical and life sciences



ORNL's major S&T initiatives

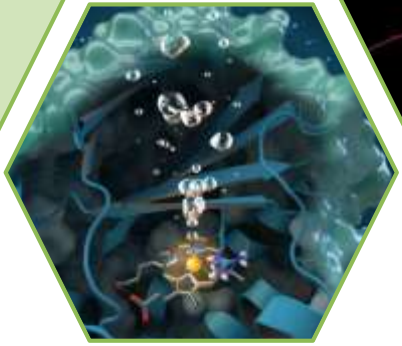
Advance ORNL's science and innovation culture



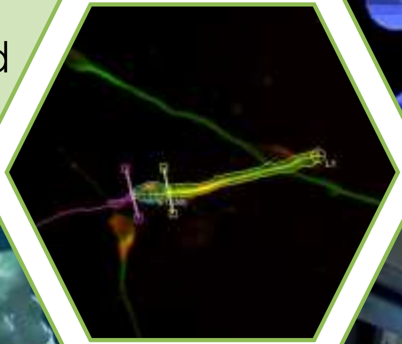
Accelerate the discovery and design of new materials for energy

Advance the science and impact of neutrons

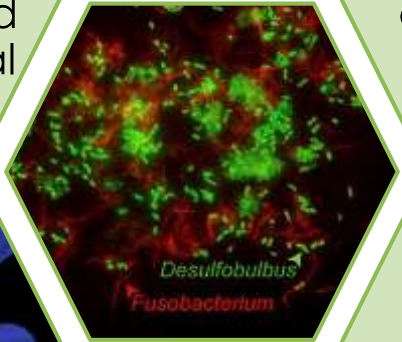
Scale computing and data analytics to exascale and beyond



Advance scientific basis for break-through nuclear technologies and systems



Advance understanding of complexity in biological and environmental systems



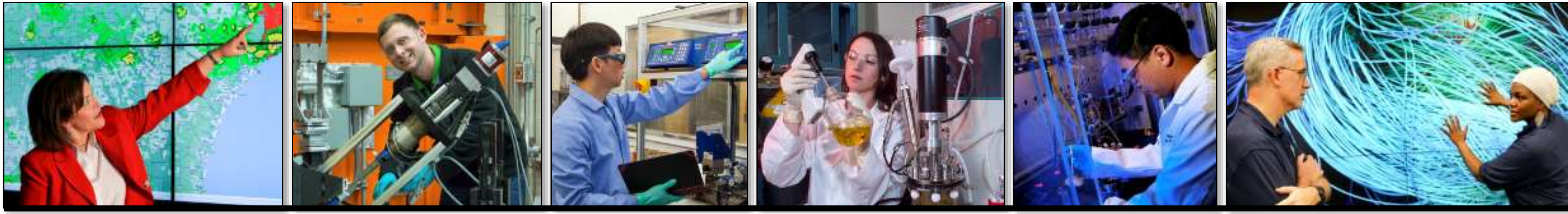
Enhance strategic capabilities in isotopes

Accelerate deployment of DOE IP and engagement with universities and industry

Accelerate R&D and manufacturing of integrated energy systems

Deliver S&T to address complex security challenges

ORNL's distinctive facilities bring thousands of R&D partners to Tennessee each year



Building Technologies Research and Integration Center

Carbon Fiber Technology Facility

Center for Nanophase Materials Sciences

High Flux Isotope Reactor

Manufacturing Demonstration Facility

National Transportation Research Center

Oak Ridge Leadership Computing Facility

Spallation Neutron Source

Today, ORNL is a leading science and energy laboratory

$1.63B
FY18 expenditures

4,600
employees

$750M
modernization investment

Nation's largest materials research portfolio

3,200
research guests annually

Nation's most diverse energy portfolio

Forefront scientific computing facilities

World's most intense neutron source

World-class research reactor

2,337
journal articles published in CY18

Managing major DOE projects:
US ITER, exascale computing

258
invention disclosures in FY18

60
patents issued in FY18

Exciting Physics

- Super Heavy Elements
- Neutrinos
- Fundamental symmetries
- Quantum computing
- Isotopes

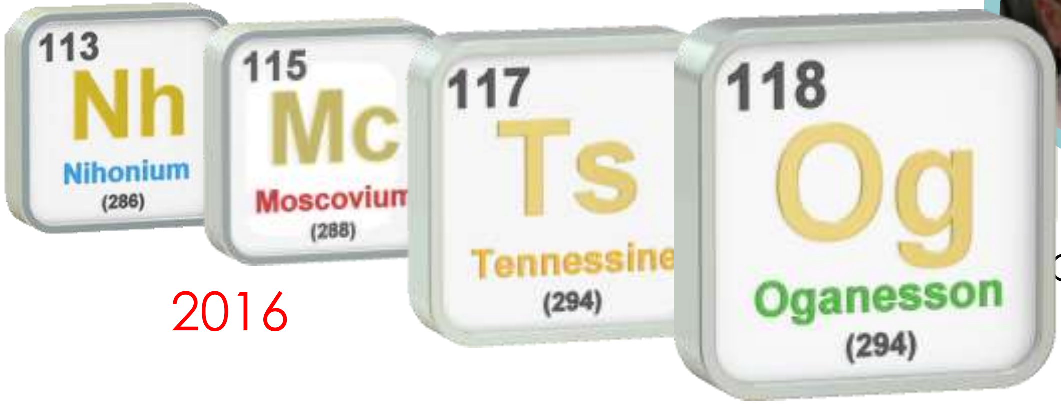
"Hot fusion" using ^{48}Ca beams on actinide targets: 6 super-heavy elements since 2000

ORNL actinides involved in all of these discoveries

Element	Nihonium (113)	Flerovium (114)	Moscovium (115)	Livermorium (116)	Tennessine (117)	Oganesson (118)
Year produced	2004	2000	2004	2005	2010	2006
Target	^{243}Am (decay from 115)	^{244}Pu	^{243}Am	^{245,248}Cm	^{249}Bk	^{249}Cf
Beam	^{48}Ca	^{48}Ca	^{48}Ca	^{48}Ca	^{48}Ca	^{48}Ca
Nuclei produced to date	140	99	135	35	22	5

2012

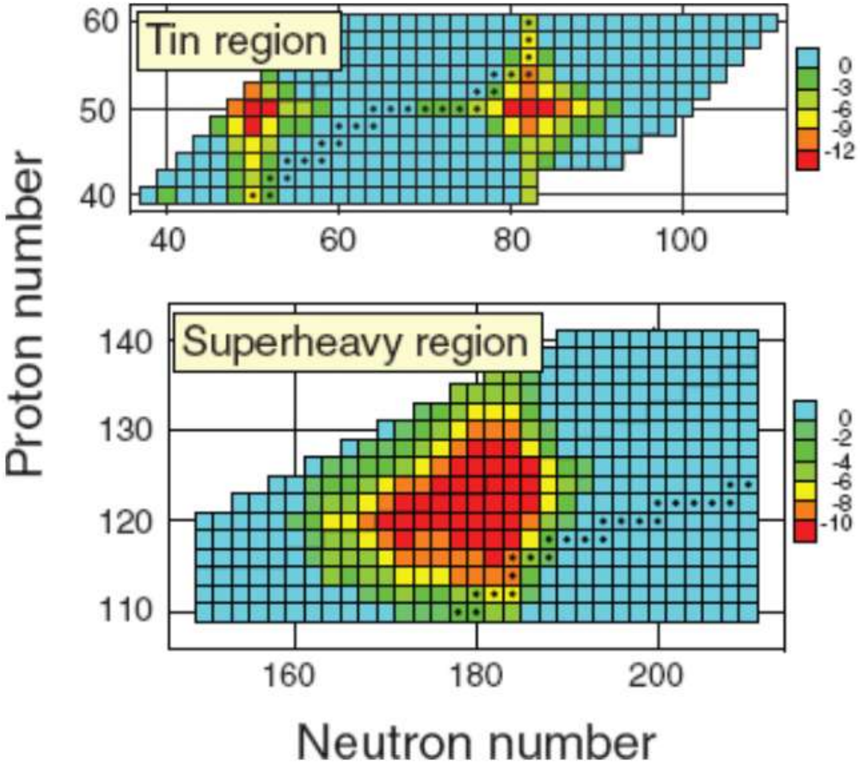
- >50 new isotopes
- >200 decay chains
- Hot fusion increases SHE production rates for Z ≥ 113 by one or more orders of magnitude



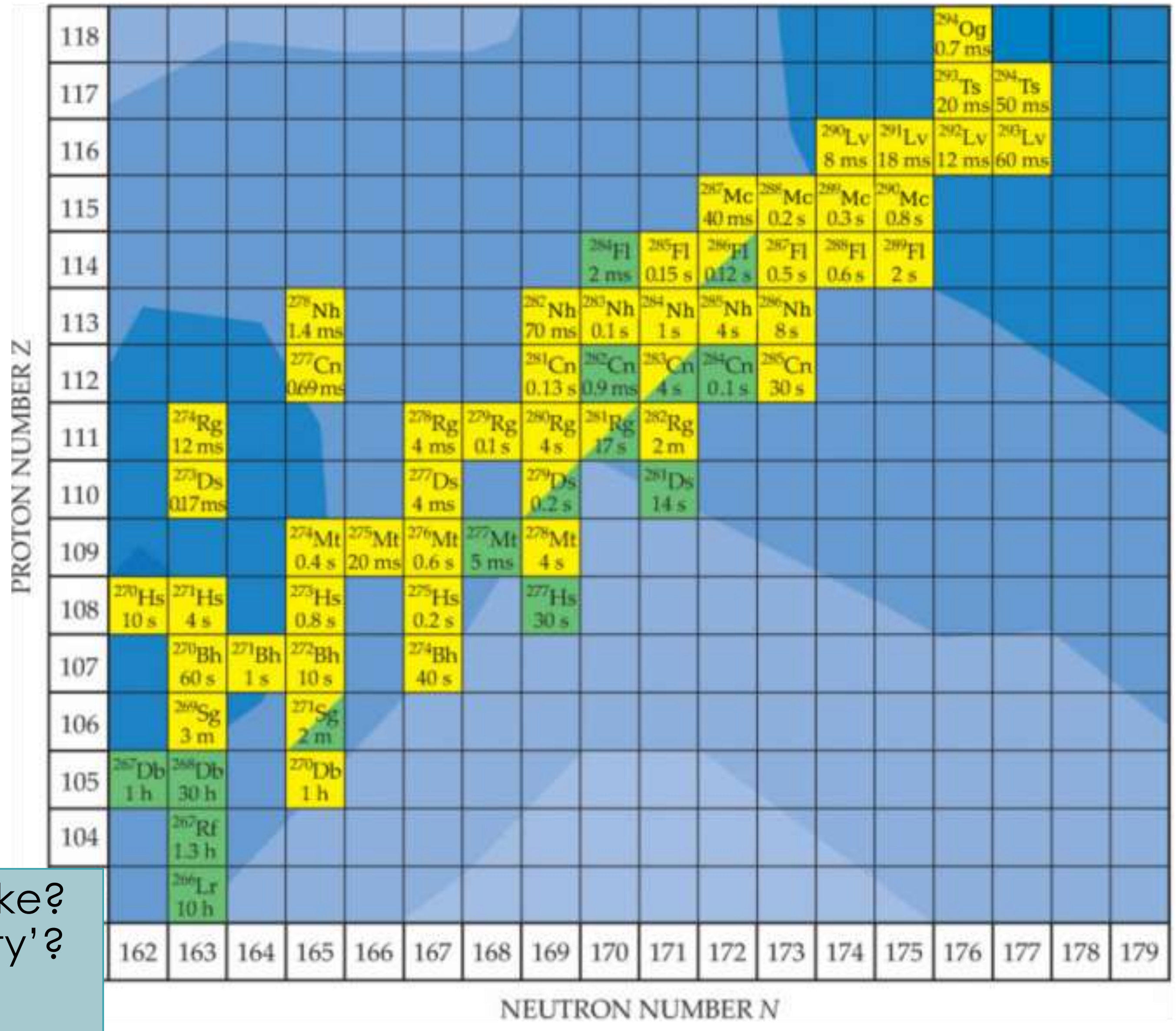
2016

Yuri Oganessian

The physics of SHE



Binder et al., PLB 515, 42 (2001)



Z \ N	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179
118															^{294}Og 0.7 ms			
117															^{293}Ts 20 ms	^{294}Ts 50 ms		
116													^{290}Lv 8 ms	^{291}Lv 18 ms	^{292}Lv 12 ms	^{293}Lv 60 ms		
115											^{287}Mc 40 ms	^{288}Mc 0.2 s	^{289}Mc 0.3 s	^{290}Mc 0.8 s				
114									^{284}Fl 2 ms	^{285}Fl 0.15 s	^{286}Fl 0.12 s	^{287}Fl 0.5 s	^{288}Fl 0.6 s	^{289}Fl 2 s				
113				^{278}Nh 1.4 ms				^{282}Nh 70 ms	^{283}Nh 0.1 s	^{284}Nh 1 s	^{285}Nh 4 s	^{286}Nh 8 s						
112				^{277}Cn 0.69 ms				^{281}Cn 0.13 s	^{282}Cn 0.9 ms	^{283}Cn 4 s	^{284}Cn 0.1 s	^{285}Cn 30 s						
111		^{274}Rg 12 ms				^{278}Rg 4 ms	^{279}Rg 0.1 s	^{280}Rg 4 s	^{281}Rg 17 s	^{282}Rg 2 m								
110		^{273}Ds 0.17 ms				^{277}Ds 4 ms		^{279}Ds 0.2 s		^{281}Ds 14 s								
109				^{274}Mt 0.4 s	^{275}Mt 20 ms	^{276}Mt 0.6 s	^{277}Mt 5 ms	^{278}Mt 4 s										
108	^{270}Hs 10 s	^{271}Hs 4 s		^{273}Hs 0.8 s		^{275}Hs 0.2 s		^{277}Hs 30 s										
107		^{270}Bh 60 s	^{271}Bh 1 s	^{272}Bh 10 s		^{274}Bh 40 s												
106		^{269}Sg 3 m		^{271}Sg 2 m														
105	^{267}Db 1 h	^{268}Db 30 h		^{270}Db 1 h														
104		^{267}Rf 1.3 h																
		^{266}Lr 10 h																

- What is the heaviest isotope we can make?
- What are the N, Z of the 'Island of Stability'?
  - N=184
  - Z=114, 120, 126?
- How do SHE lifetimes evolve?

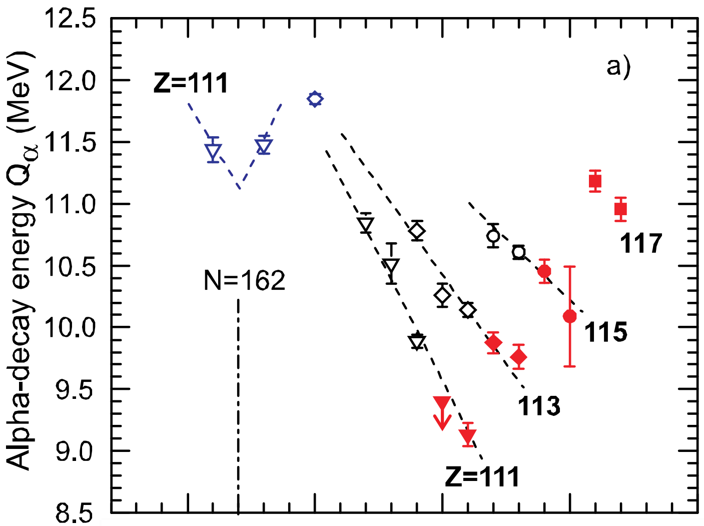
New isotopes from element 117 decay chains show consistent behavior across Z and N

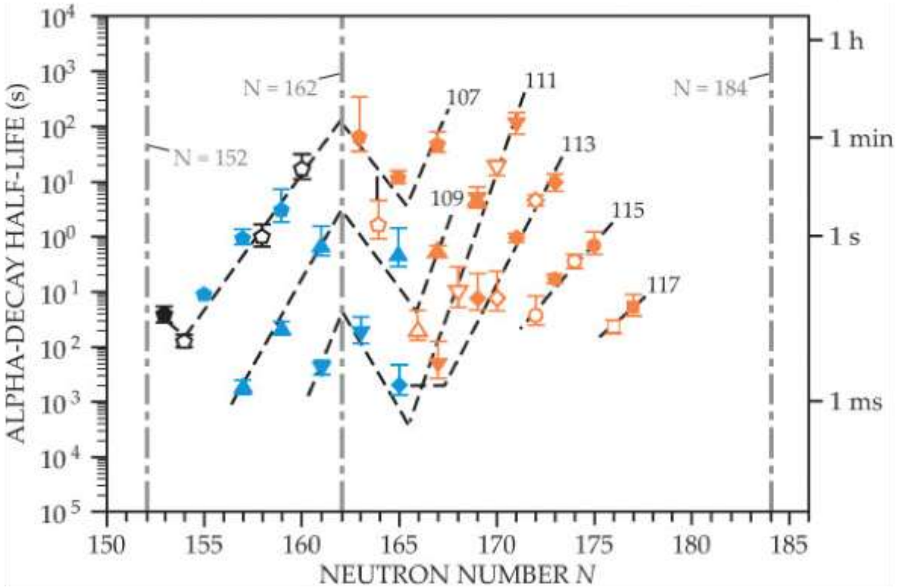
Closer approach to closed shell at N = 184 results in decreased α-decay energy and increased lifetime

Continued trend toward increasing stability for higher neutron numbers

Strong evidence for the “Island of Stability”

A self-consistent picture of decay properties has emerged

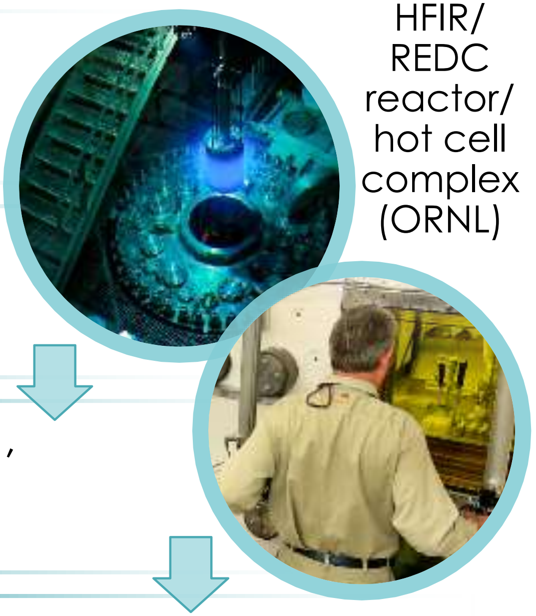




International collaboration was essential

What it took to produce a few atoms of Tennessine

3 g of Ca-48	Natural abundance enriched 500 times at Sverdlovsk-45
20 mg of Bk-249	Produced by 250-day neutron irradiation in the world's highest thermal neutron flux at ORNL's High Flux Isotope Reactor
Chemical separation of Bk from irradiated targets	Impurities less than 2 ng (1 part in 10^7), performed at ORNL's Radiochemical Engineering Development Center
Preparation of Bk target foils	Specially produced at Dimitrovgrad to survive massive ion bombardment
Target irradiation with Ca-48	150 days continuous irradiation in the world's most intense Ca-48 beam at the Flerov Laboratory in Dubna



HFIR/
REDC
reactor/
hot cell
complex
(ORNL)

Flerov Laboratory (Dubna)

Towards new atomic elements 119 and 120: joint experiments US-Russia and US-Japan on super heavy elements and nuclei

- There are several large scale investigations planned for years 2018-2022 involving US, Russia and Japan laboratories and aiming in the discoveries of new super heavy nuclei including isotopes of new elements 119 and 120.

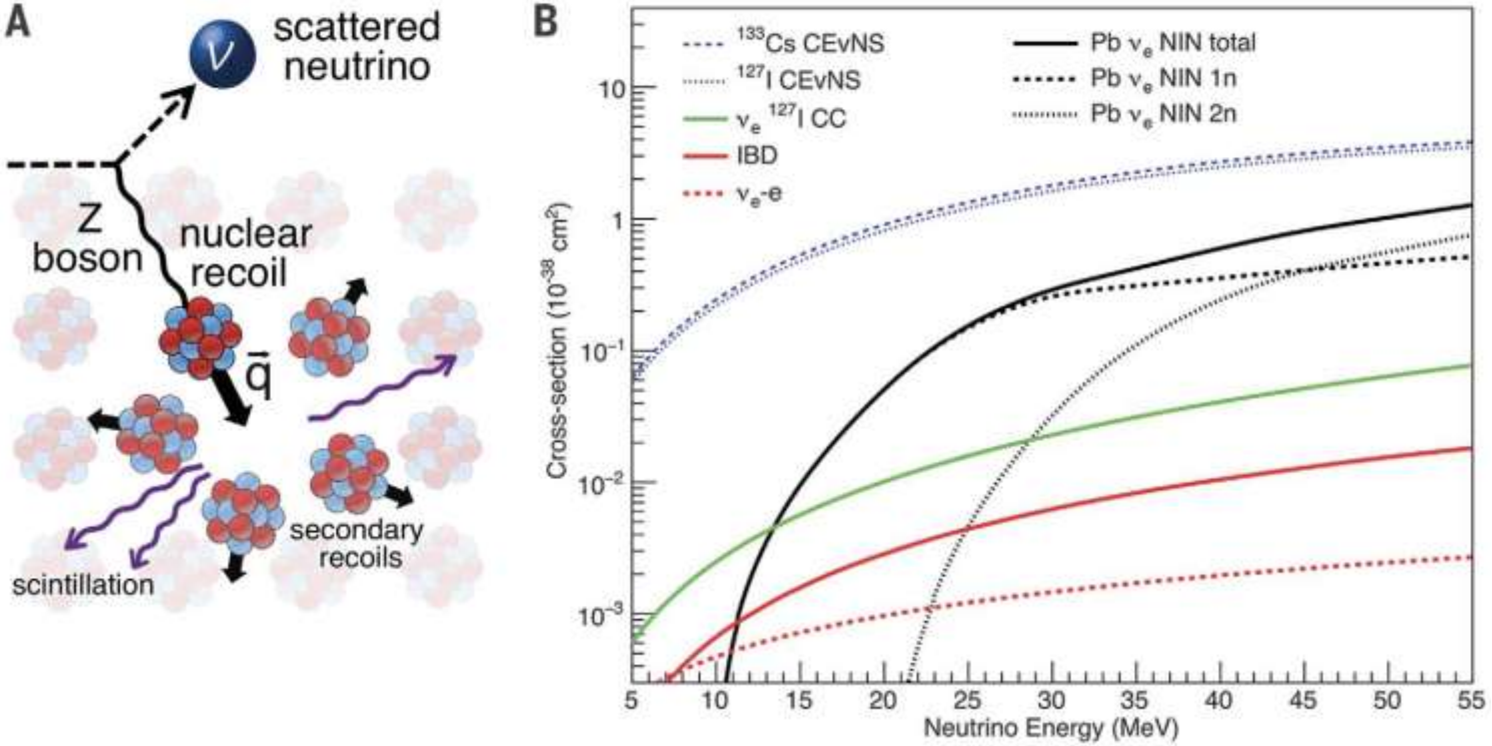
- The elements 119 and 120 will start a new row in the Periodic Table and allow us to study the properties of atoms and nuclei affected by the strongest Coulomb fields.

- The US-Russia experiments employing Z=22 ^{50}Ti beams at the new SHE Factory require Z=97 ^{249}Bk and Z=98 mixed-Cf targets to reach Z=119 and Z=120, respectively.

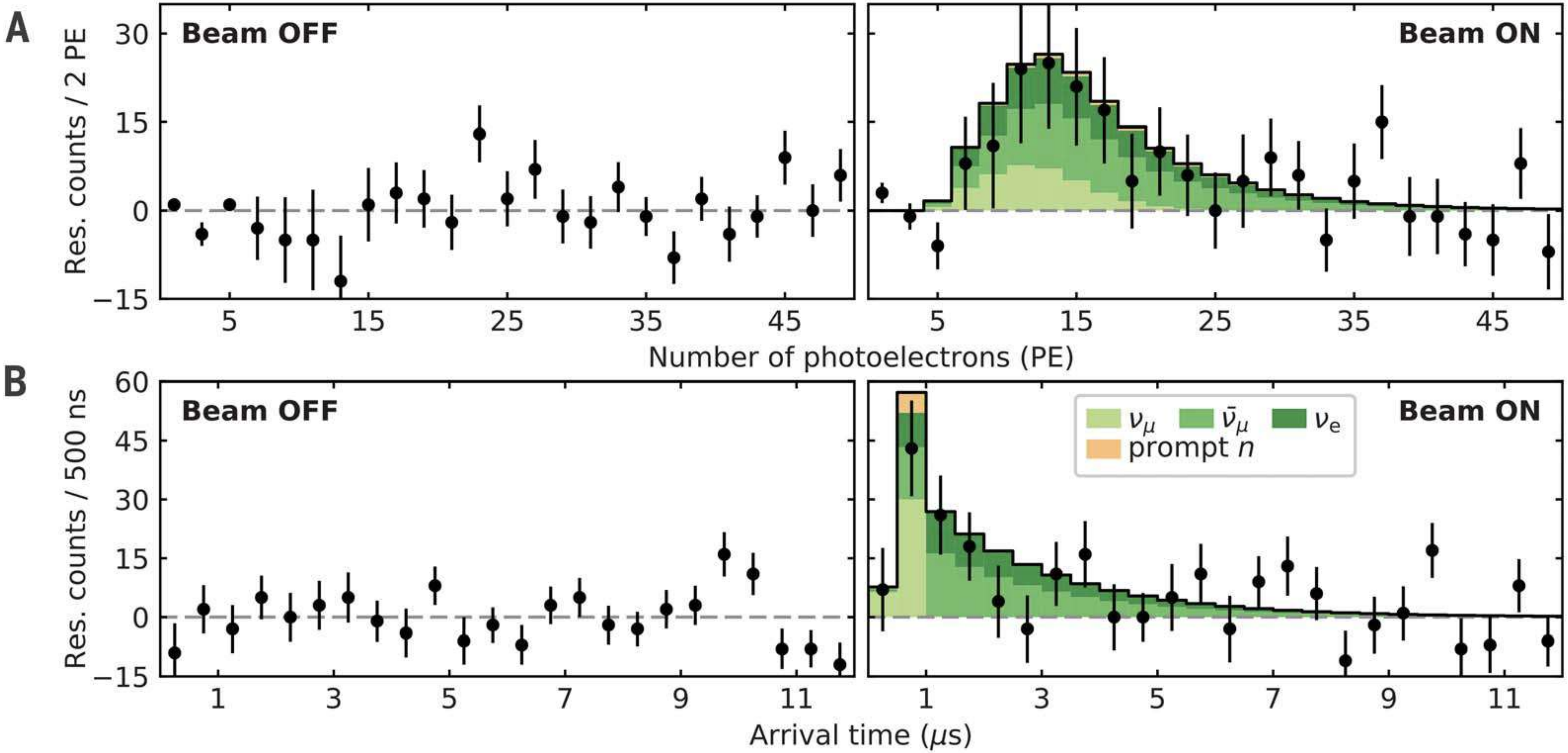
- The US-Japan experiments will use Z=96 ^{248}Cm targets and beams of Z=23 ^{51}V and Z=24 ^{54}Cr , respectively, to synthesize elements Z=119 and Z=120 at two new SHE-dedicated accelerator-separator facilities at RIKEN.

- Both experiments employ heavy ions beams of high intensity requiring large target area to dissipate heat , about ~ 20 mg (RIKEN) and ~ 30 mg (SHE Factory) of respective actinide material deposited on target wheels rotating at high speed.

Coherent neutrino scattering

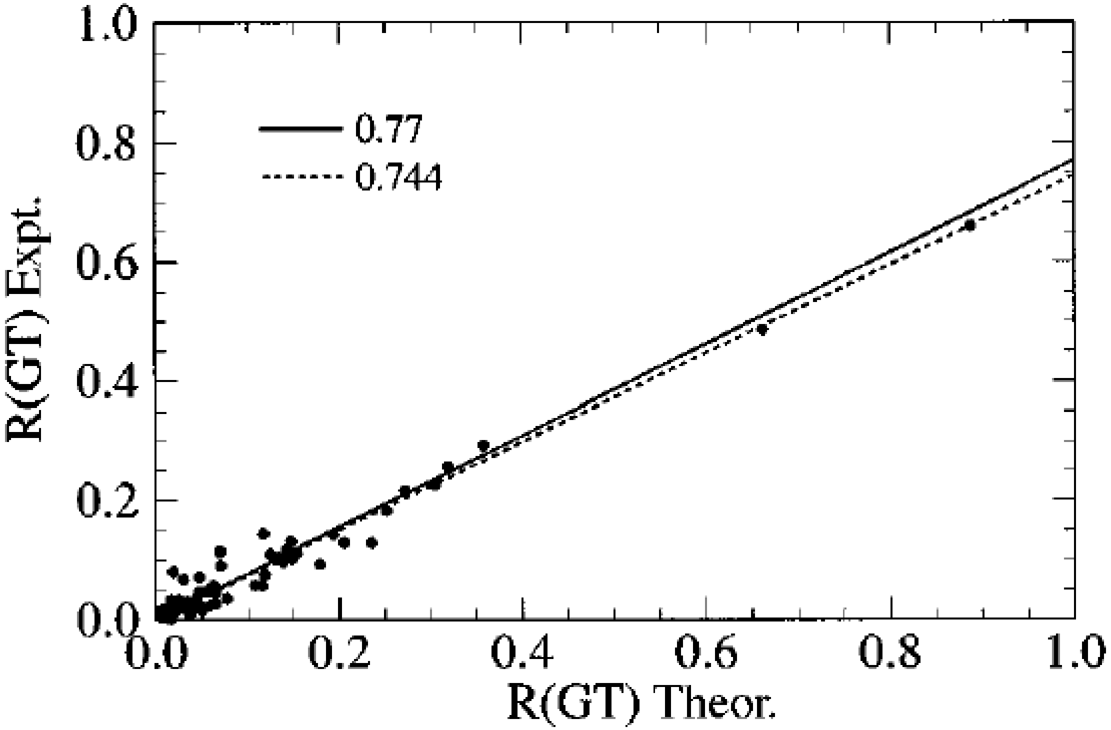


Coherent Neutrino Scattering



Akimov et al., *Science* 357, 1123 (2017)

Quenching of Gamow-Teller strength in nuclei



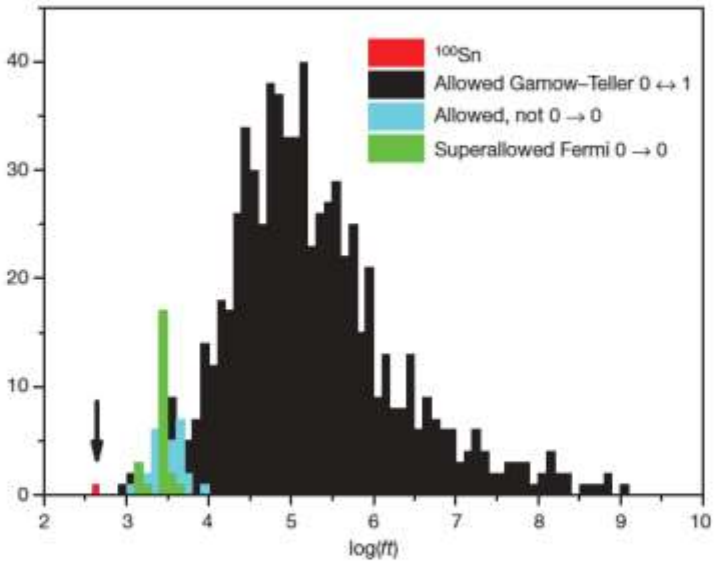
G. Martinez-Pinedo et al, PRC **53**, R2602 (1996)

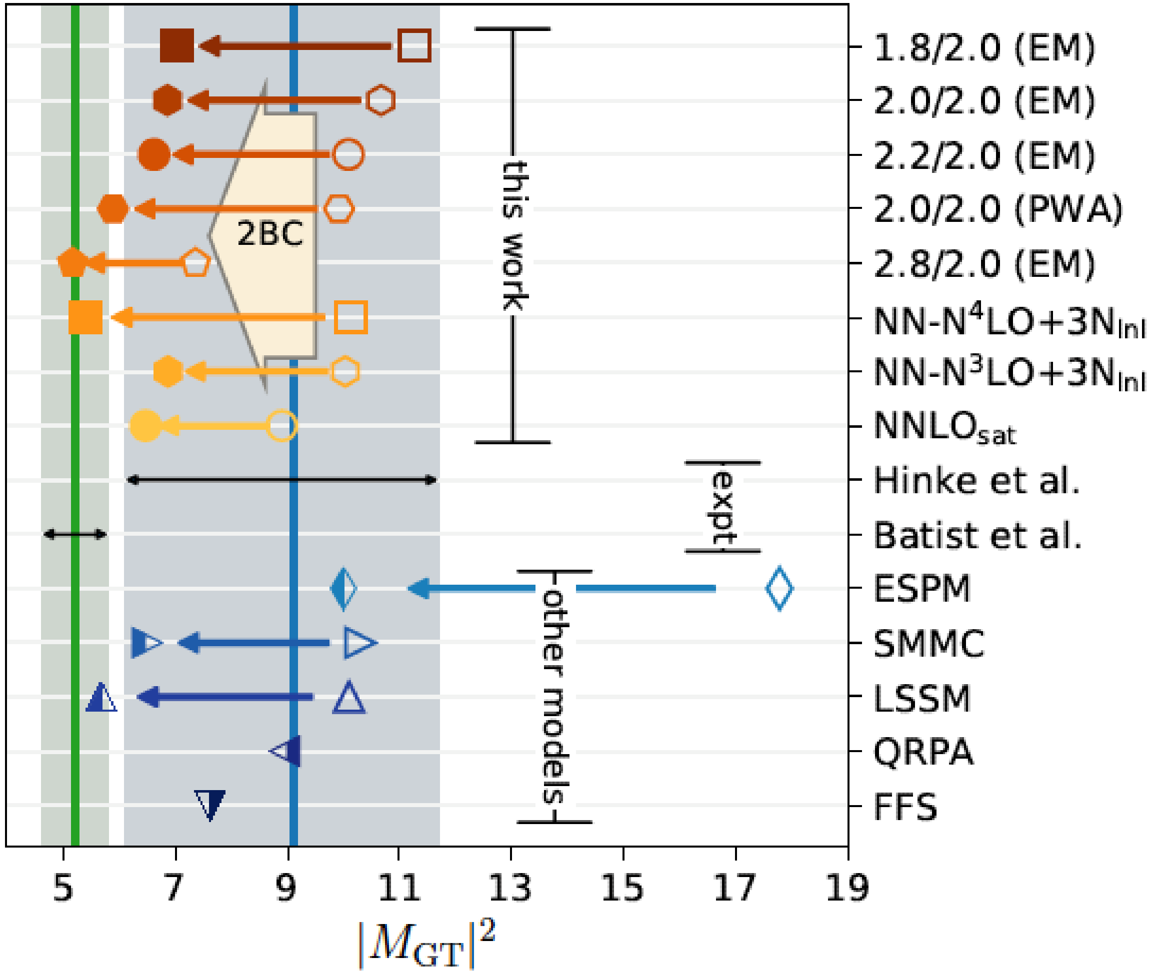
Renormalizations of the Gamow-Teller operator?
Missing correlations in nuclear wave functions?
Model-space truncations?

-→ Perform ab initio computations (Coupled cluster theory)

The quenching puzzle of β decays: ^{100}Sn

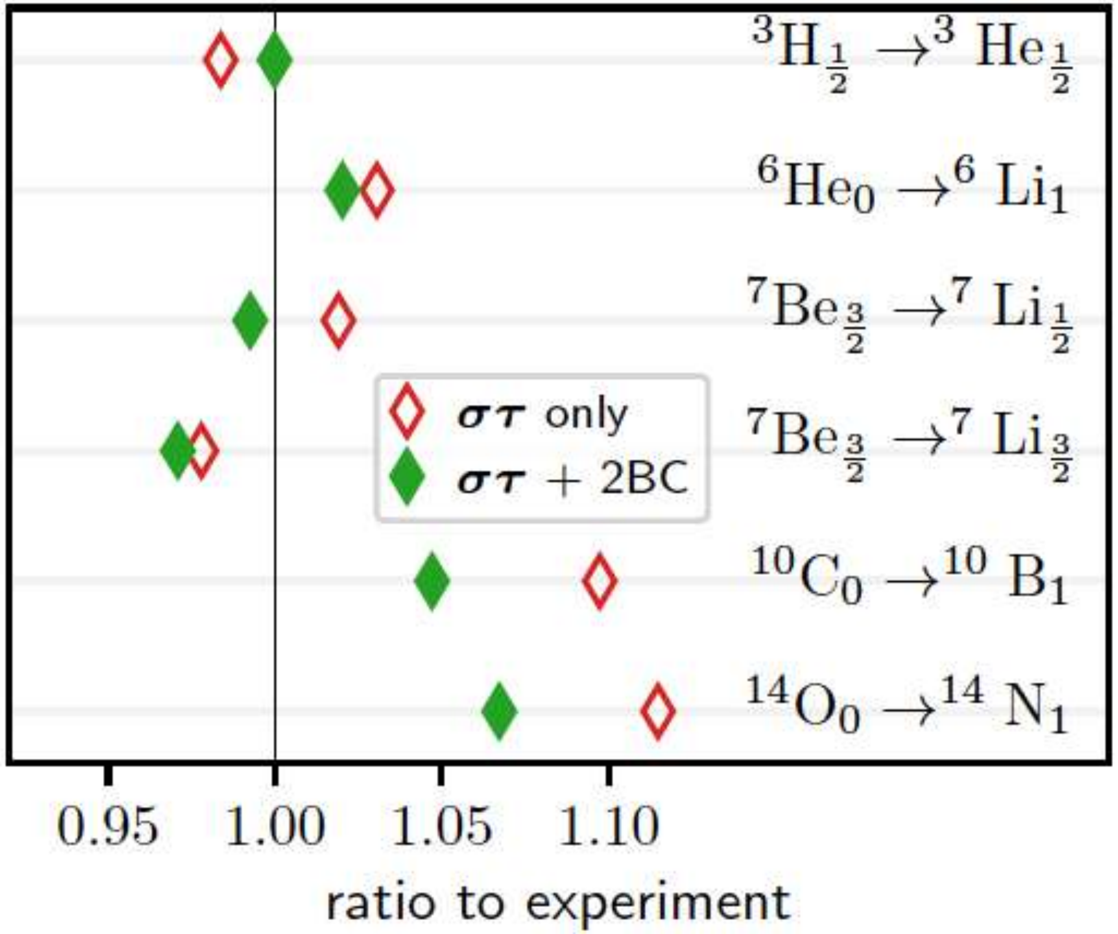
Hinke et al, Nature (2012):
^{100}Sn has strongest beta decay GT matrix element





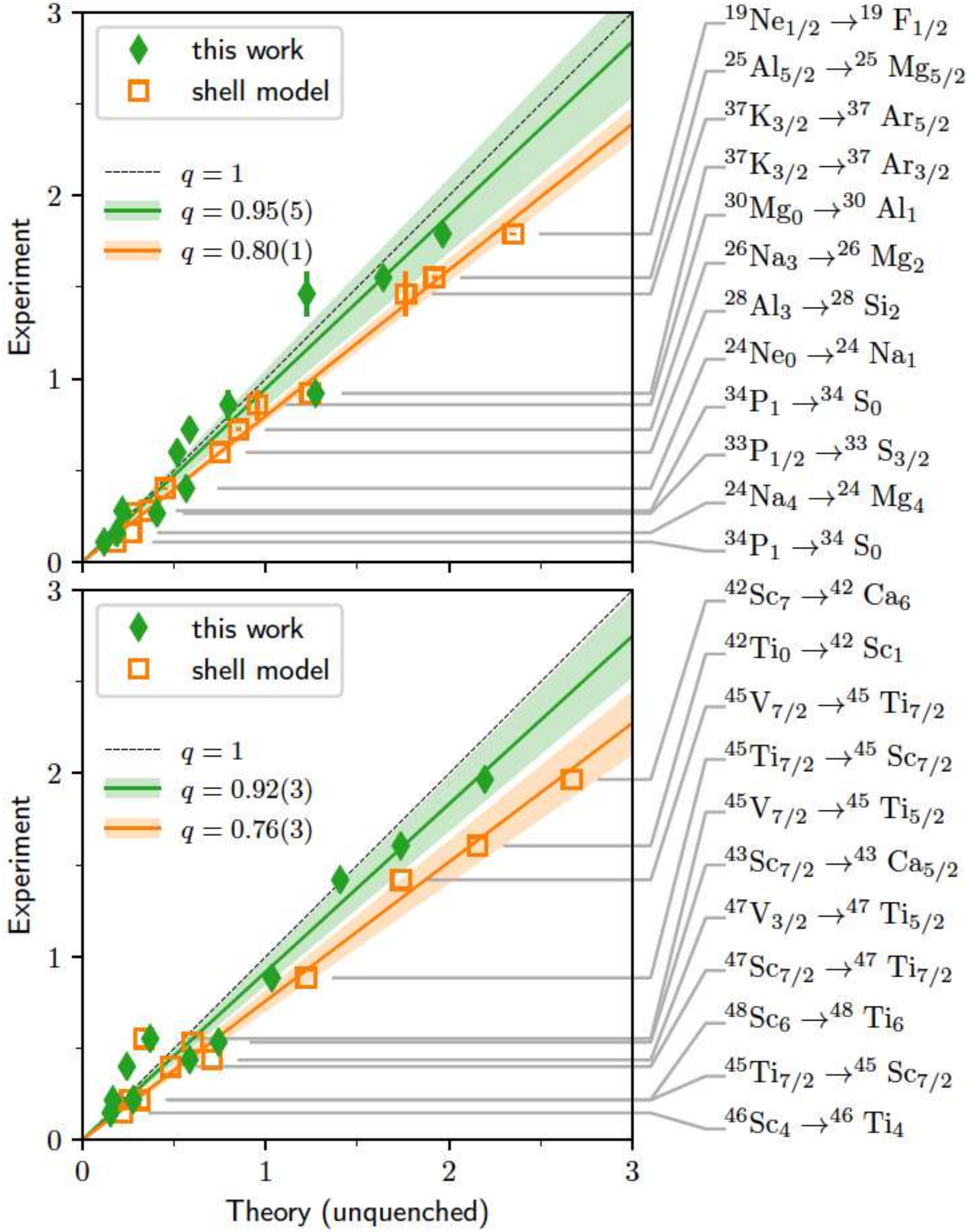
P. Gysbers, G. Hagen, J. D. Holt, G. R. Jansen, T. D. Morris, P. Navrátil, T. Papenbrock, S. Quaglioni, A. Schwenk, S. R. Stroberg & K. A. Wendt, Nature Physics (2019)

The quenching puzzle of β decays: light nuclei



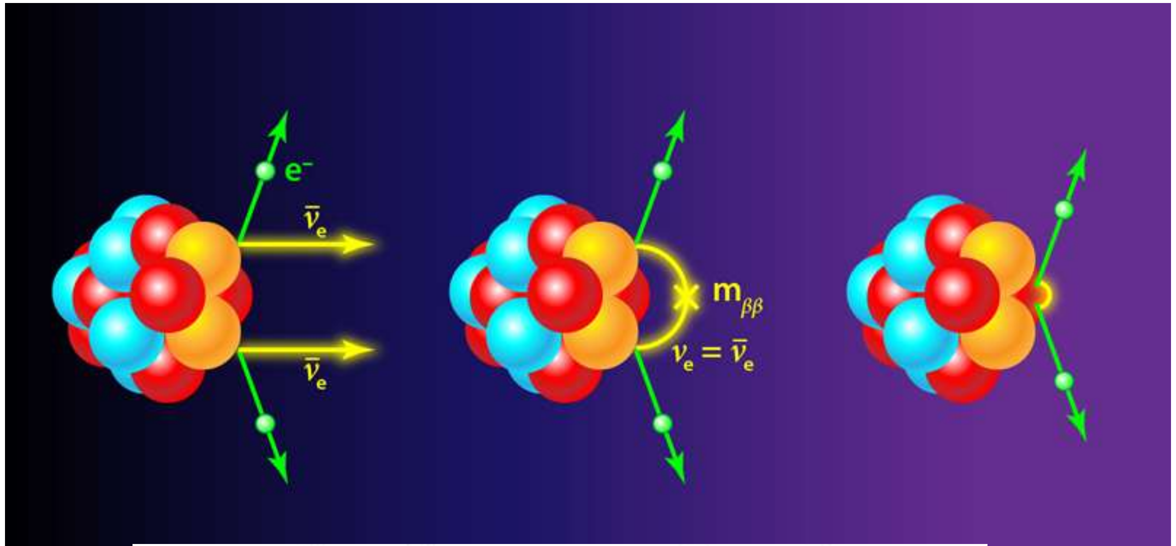
In light nuclei, two-body currents slightly improve agreement with data

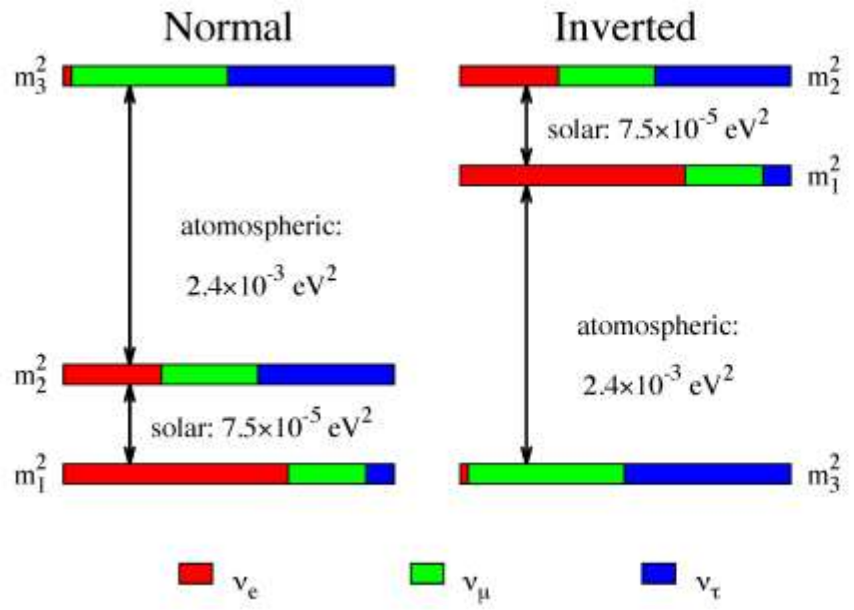
The quenching puzzle of β decays: sd and pf shell

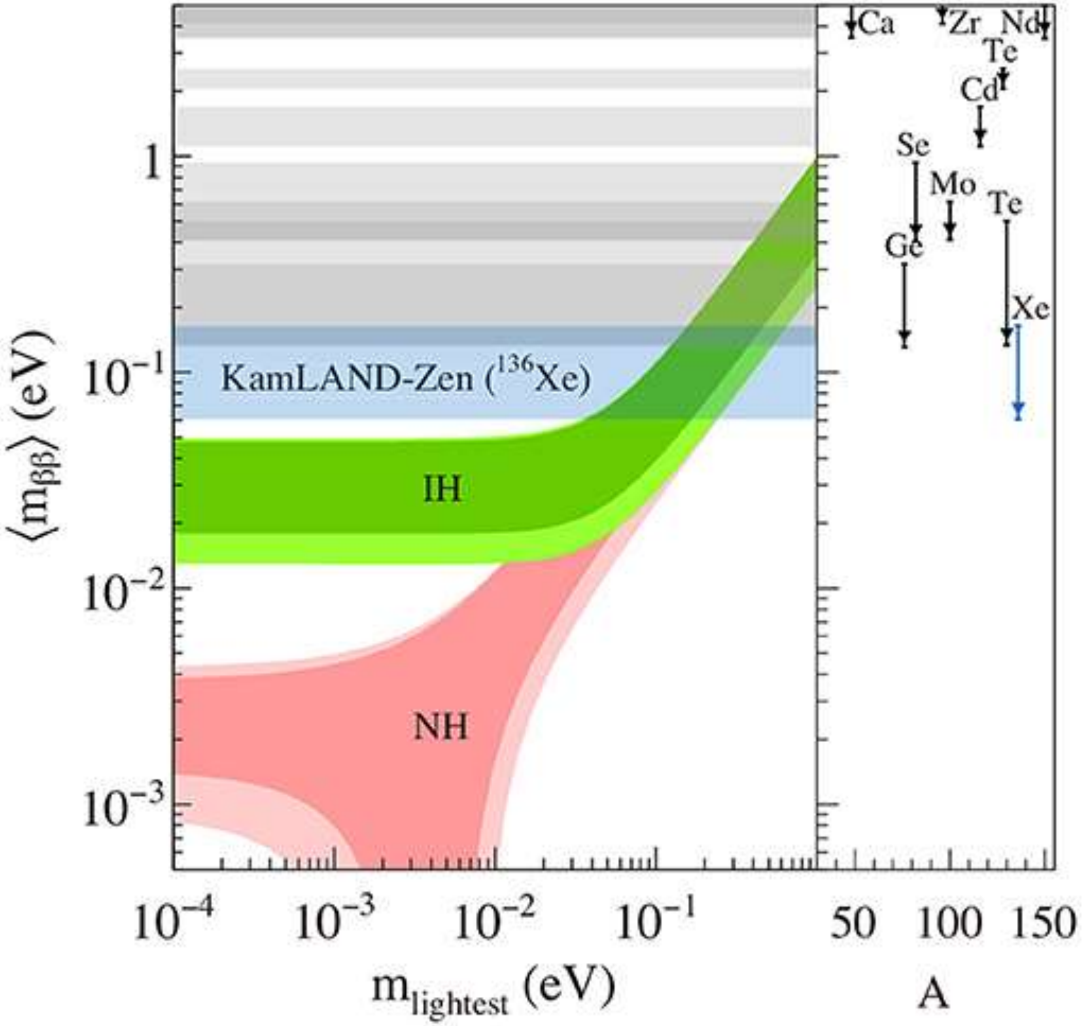


Improved dscription of sd shell and pf shell nuclei.

Neutrinoless double beta decay







A. Gando et al., PRL 117, 082503 (2016)

Majorana Demonstrator

First neutrinoless double beta (0νββ) decay results from MJD

Scientific achievement

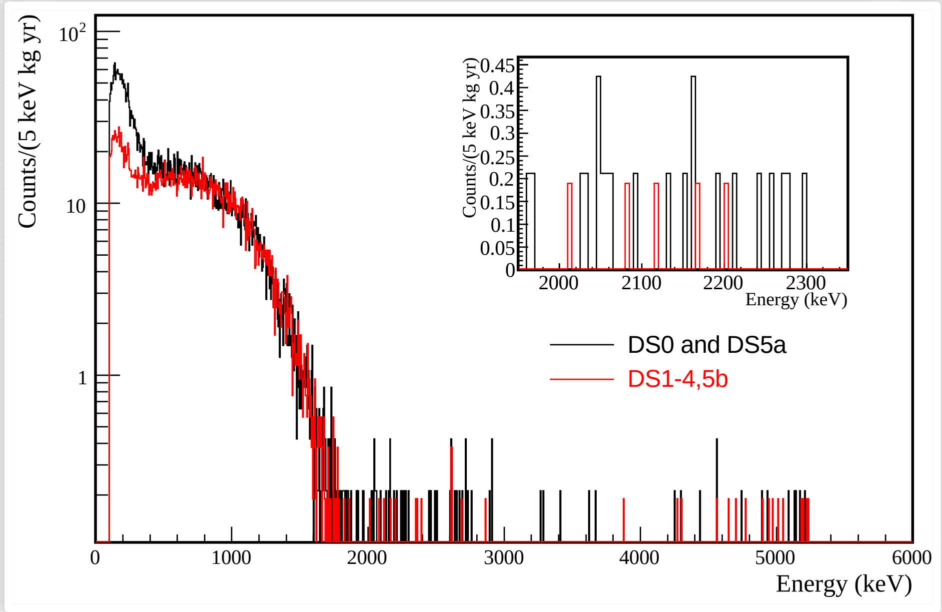
- Analysis of first Majorana Demonstrator (MJD) data (taken during construction, commissioning, and start of full operations) yields **a lower limit on the half-life of 1.9 × 10^{25} year (90% CL)**
- This result constrains the effective Majorana neutrino mass to <250 meV to 550 meV, depending on the matrix elements used
  - C. E. Aalseth et al. (Majorana Collaboration), *Phys. Rev. Lett.* **120,** 132502 (2018)

Significance and impact

- Results are consistent with MJD goal of achieving background of 2.5 counts/(FWHM t year), which would justify a large 0νββ experiment using ^{76}Ge

Research details

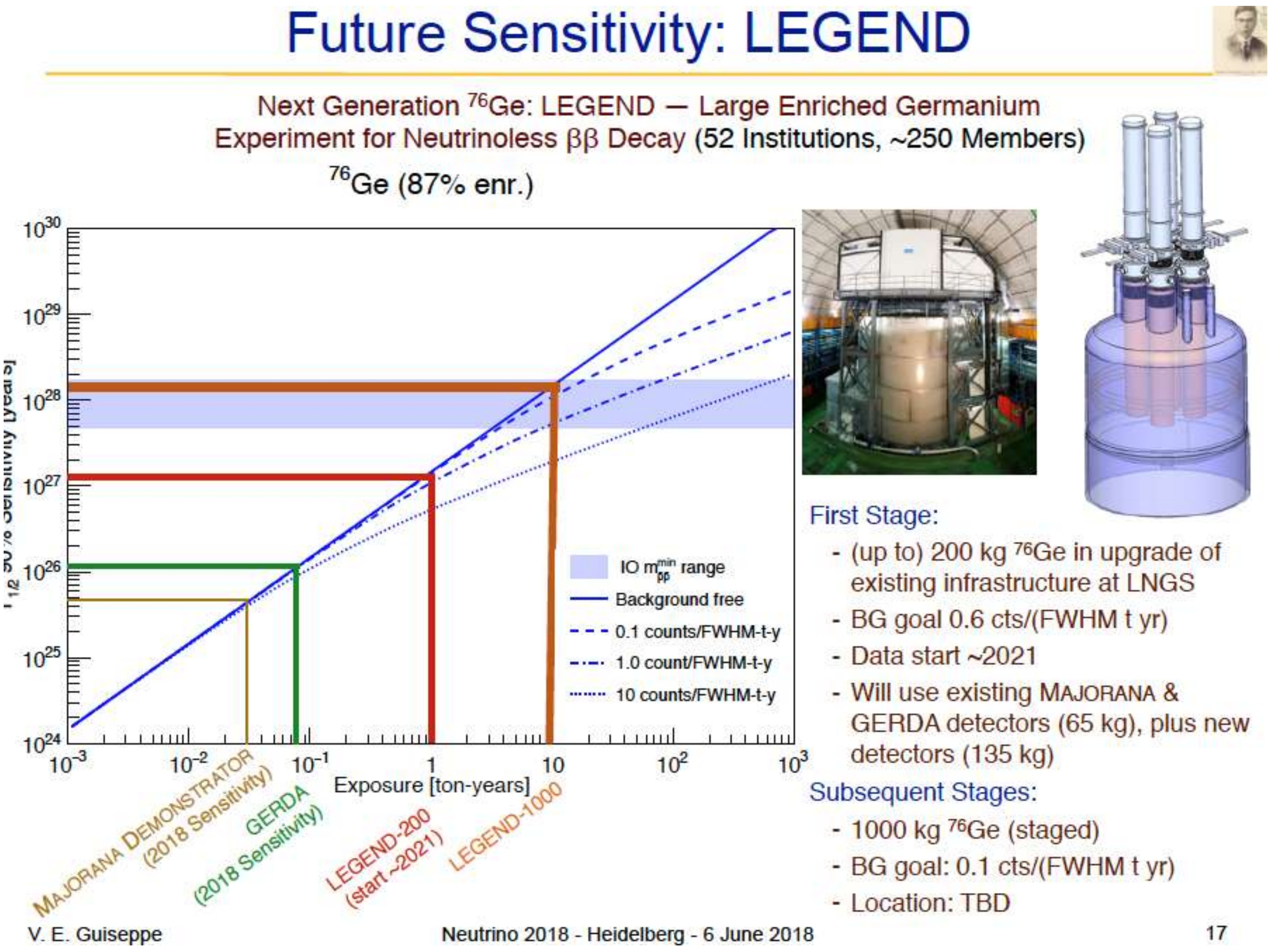
- Operating since 2016 in Sanford Underground Research Facility, MJD is searching for 0νββ decay in ^{76}Ge using 29.7 kg of detectors made from germanium enriched to 88% in that isotope



MJD spectrum above 100 keV after all cuts, from data sets with higher expected backgrounds (black) compared to data sets with lower background (red)

Future Sensitivity: LEGEND

Next Generation ^{76}Ge: LEGEND — Large Enriched Germanium Experiment for Neutrinoless ββ Decay (52 Institutions, ~250 Members)



First Stage:

- (up to) 200 kg ^{76}Ge in upgrade of existing infrastructure at LNGS
- BG goal 0.6 cts/(FWHM t yr)
- Data start ~2021
- Will use existing MAJORANA & GERDA detectors (65 kg), plus new detectors (135 kg)

Subsequent Stages:

- 1000 kg ^{76}Ge (staged)
- BG goal: 0.1 cts/(FWHM t yr)
- Location: TBD

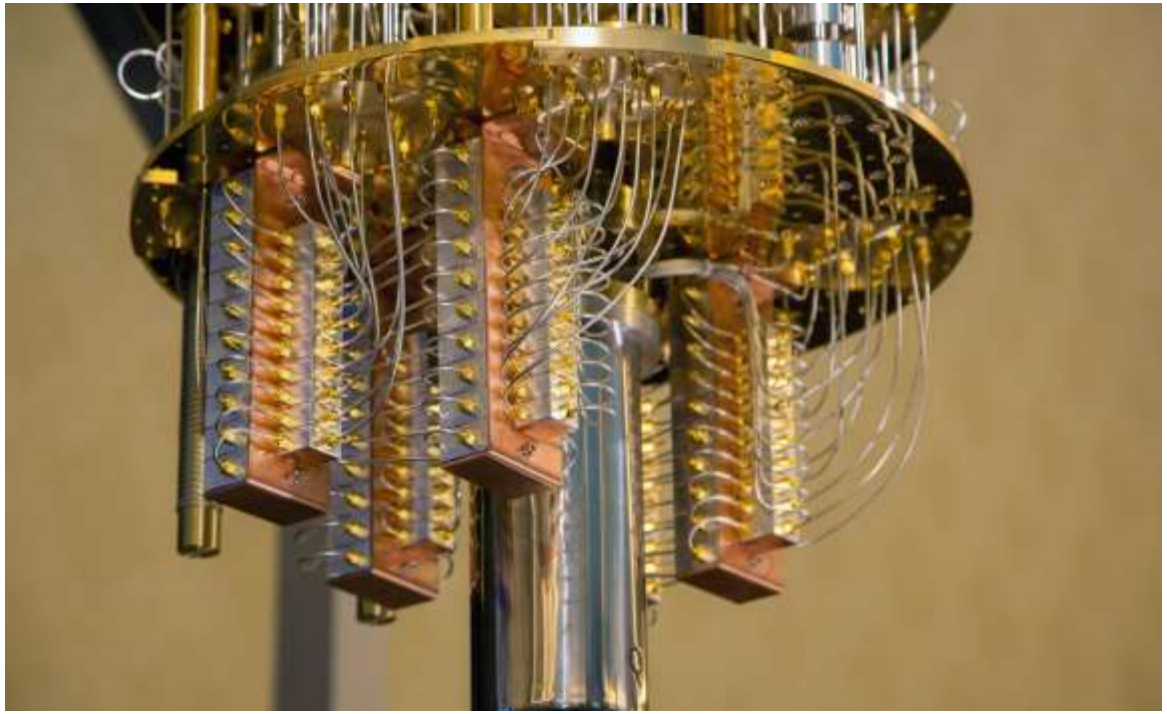
V. E. Guiseppe

Neutrino 2018 - Heidelberg - 6 June 2018

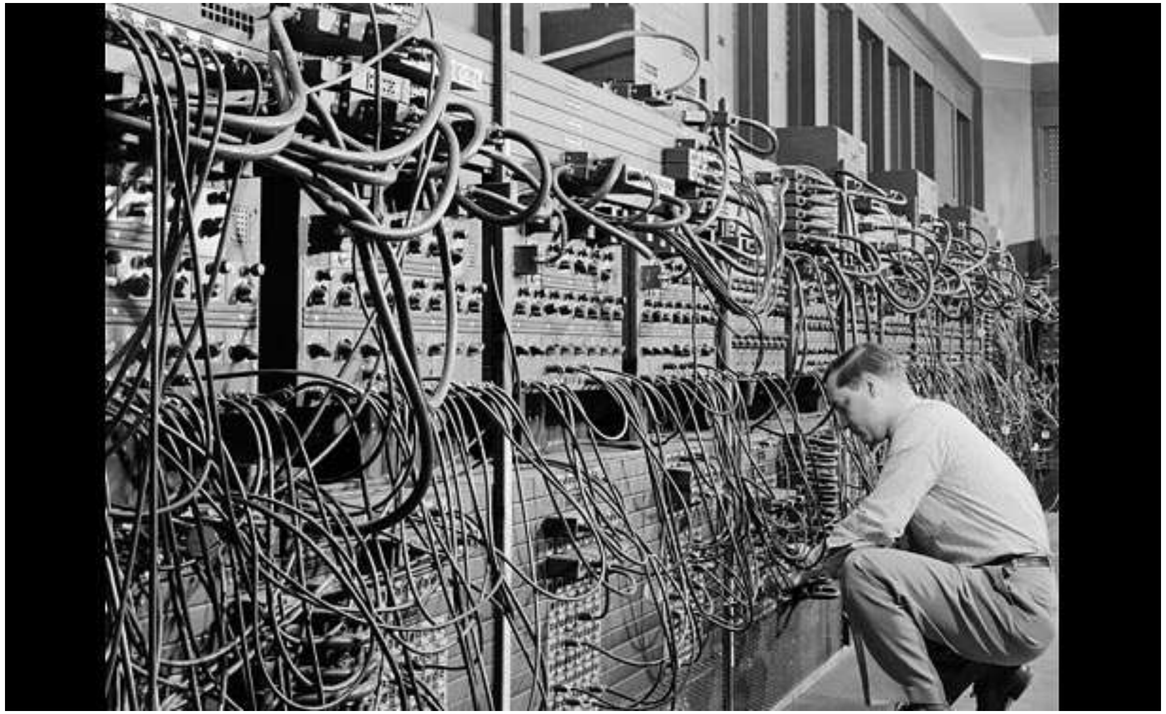
17

A brief quantum walk…

Quantum computer today



Vacuum tube computer

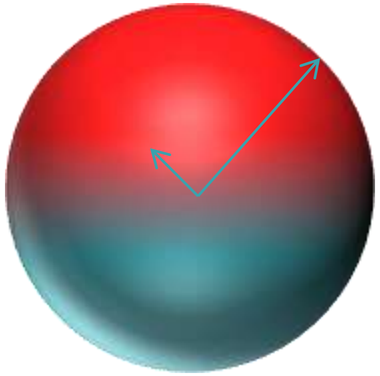


Quantum computing and its algorithms

● 1 = on

● 0 = off

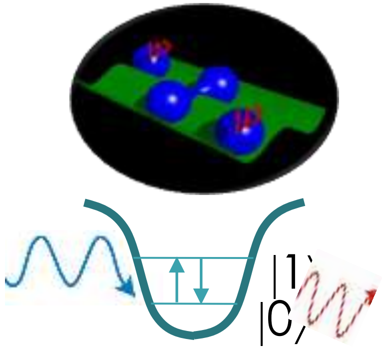
Classical:
Definite state



$|Y\rangle = a|0\rangle + b|1\rangle$

$|a|^2 + |b|^2 = 1$

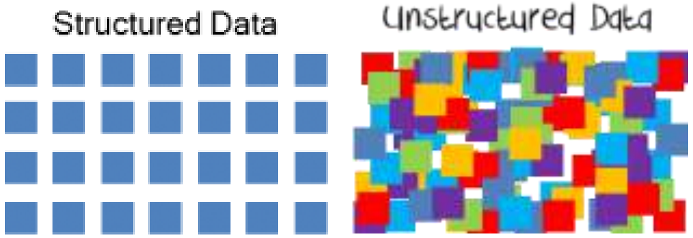
Quantum: State superposition



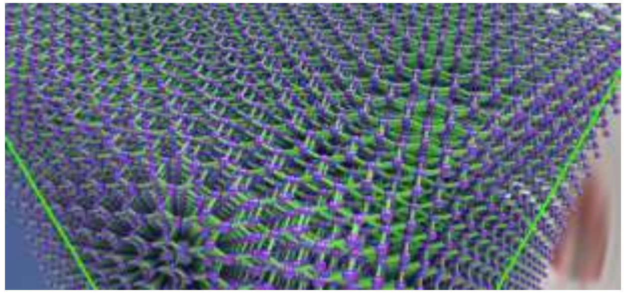
Must prepare
and probe with external fields

21=7*3

Shor's
algorithm



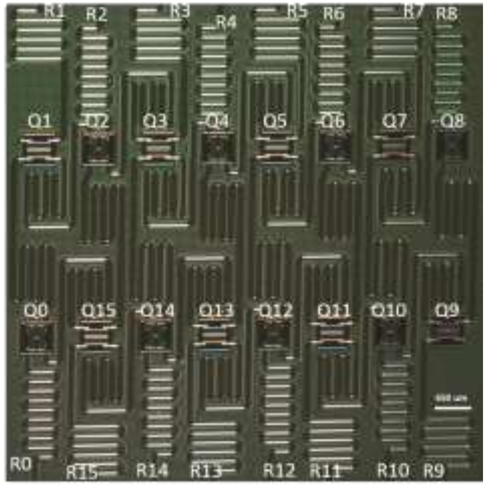
Grover's algorithm (or inversion)

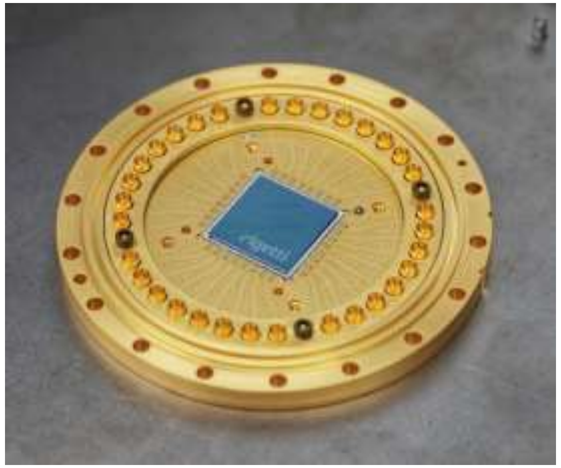


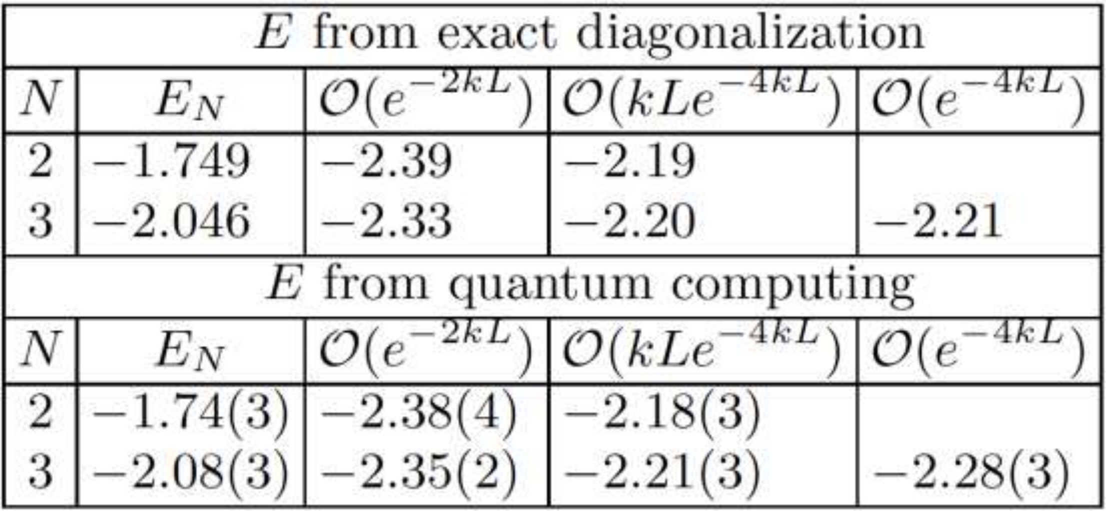
Quantum many-body
simulation: Feynman, Lloyd

~15 algorithms exist; others can be expected as QC develops

Quantum computing in the cloud



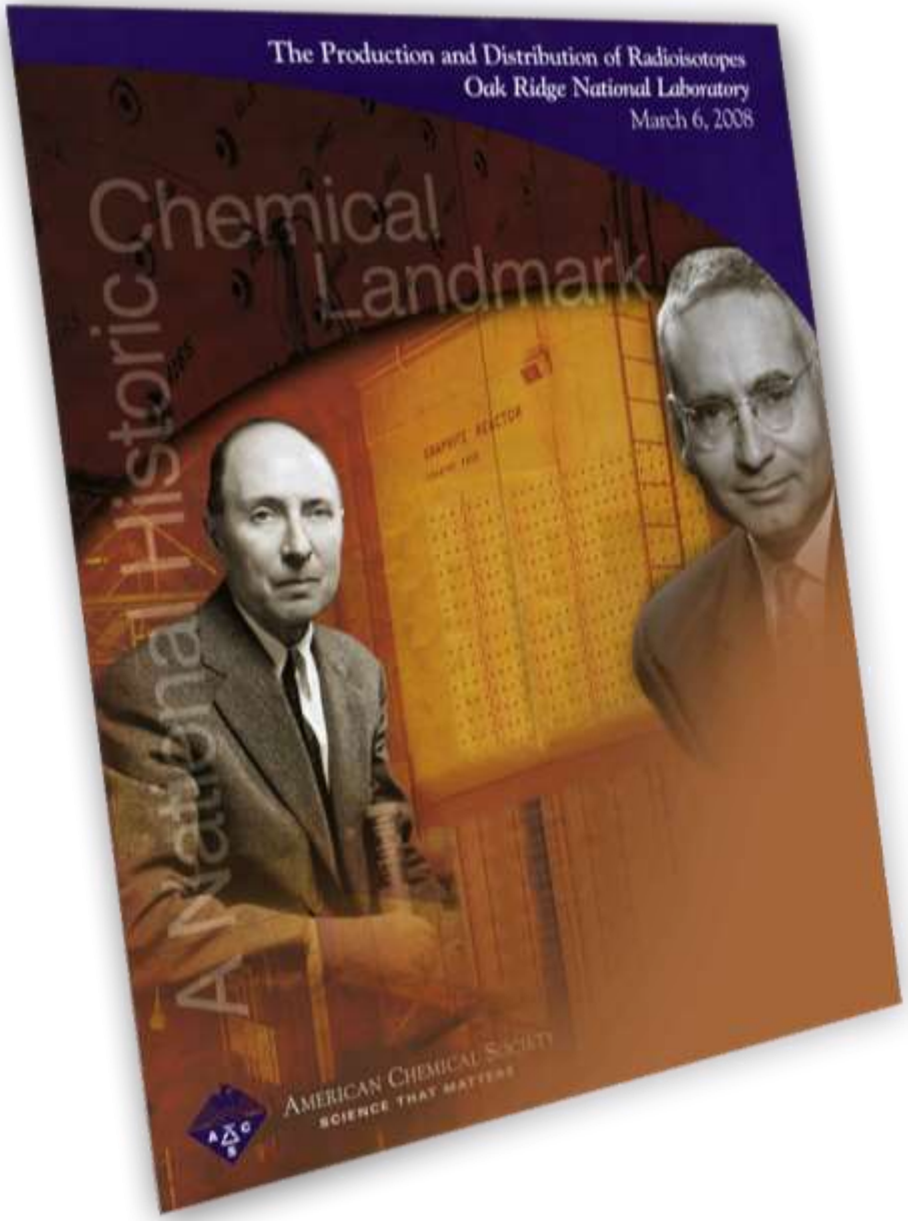




E from exact diagonalization				
N	E_N	$\mathcal{O}(e^{-2kL})$	$\mathcal{O}(kLe^{-4kL})$	$\mathcal{O}(e^{-4kL})$
2	-1.749	-2.39	-2.19	
3	-2.046	-2.33	-2.20	-2.21
E from quantum computing				
N	E_N	$\mathcal{O}(e^{-2kL})$	$\mathcal{O}(kLe^{-4kL})$	$\mathcal{O}(e^{-4kL})$
2	$-1.74(3)$	$-2.38(4)$	$-2.18(3)$	
3	$-2.08(3)$	$-2.35(2)$	$-2.21(3)$	$-2.28(3)$

Altmetric

E.F. Dumitrescu et al.,
PRL 120, 21501 (2018)



The Production and Distribution of Radioisotopes
Oak Ridge National Laboratory
March 6, 2008

A National Historic Chemical Landmark

American Chemical Society
Science That Matters

> “If at some time a heavenly angel should ask
> what the Laboratory in the hills of East Tennessee
> did to enlarge man’s life and make it better,
> I daresay the production of radioisotopes
> for scientific research and medical treatment
> will surely rate as a candidate for first place.”

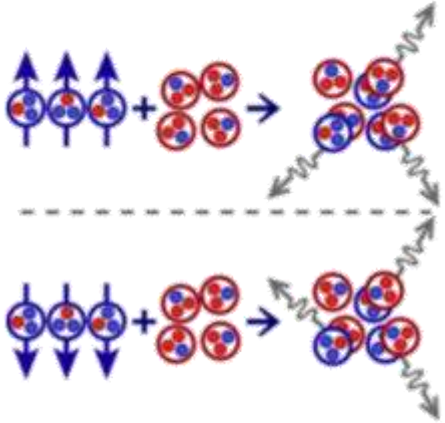
Alvin Weinberg, ORNL Director (1955–1973)

Hadronic Weak Interaction (npdγ and n^{3}He)

Editors' Suggestion

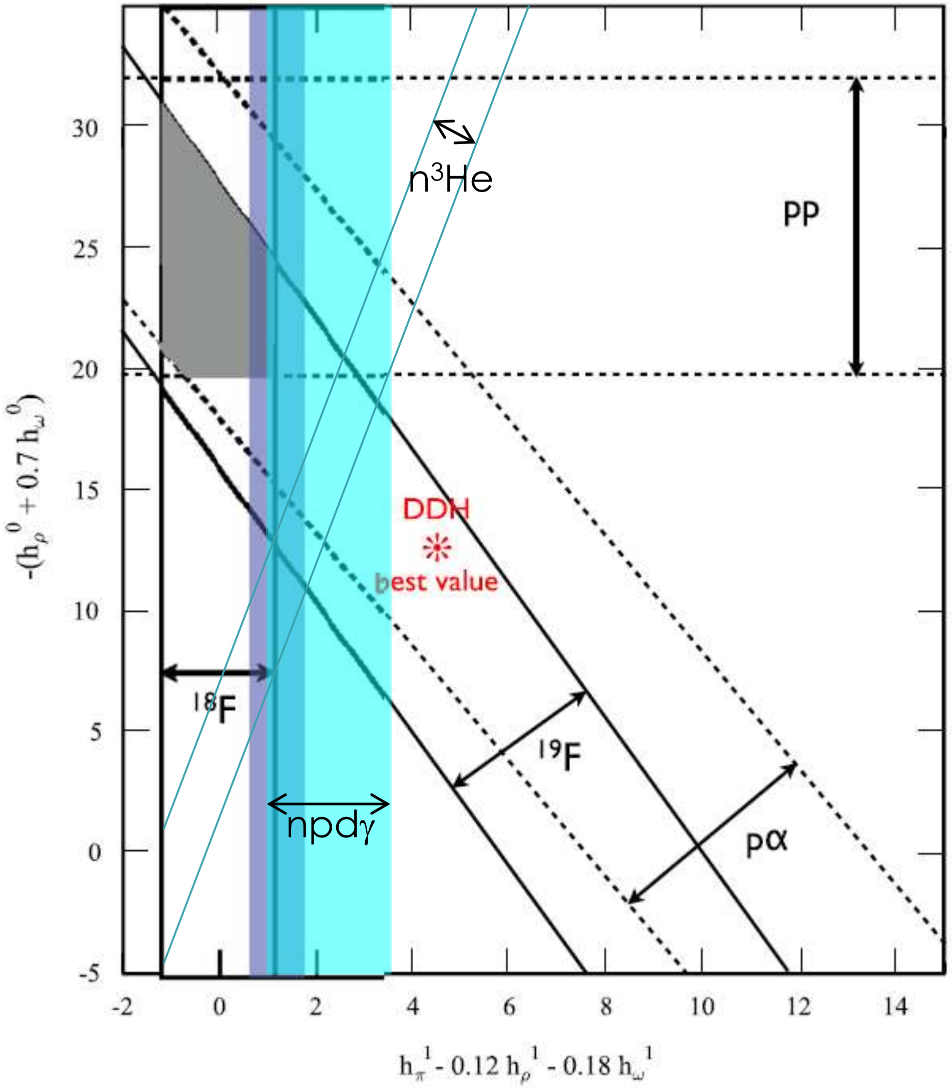
First Observation of P-odd γ Asymmetry in Polarized Neutron Capture on Hydrogen

D. Blyth *et al.* (NPDGamma Collaboration)
Phys. Rev. Lett. **121**, 242002 – Published 13 December 2018



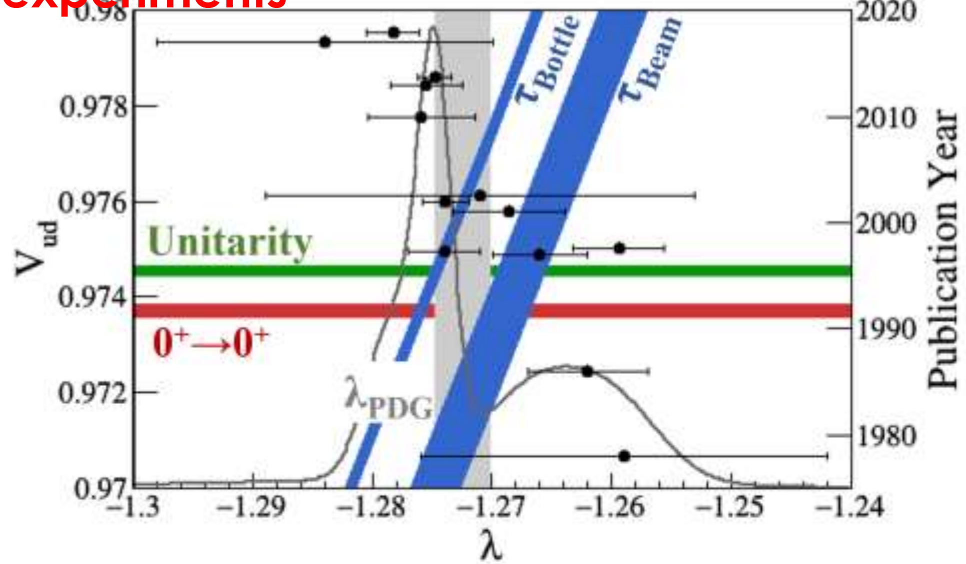
Measurement of a parity-odd asymmetry in the photons emitted from the capture of polarized neutrons on protons provided a first measurement of a weak-interaction term in the nucleon-nucleon potential.

Adapted from Haxton and Holstein, Prog. Nucl. Part. Phys., **71** 185 (2013)



The Nab Experiment

Tension in “unitarity test” of quark mixing in the weak interaction between **theory predictions** and **nuclear beta decay experiments**



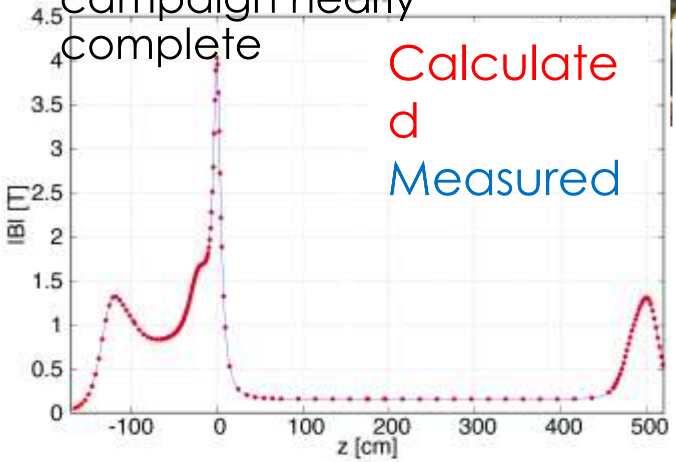
Neutron **lifetime** and **decay correlations (λ)** measurements can reveal source of discrepancy

Nab will extract λ with superior precision using completely independent approach, as well as search for exotic scalar and tensor currents

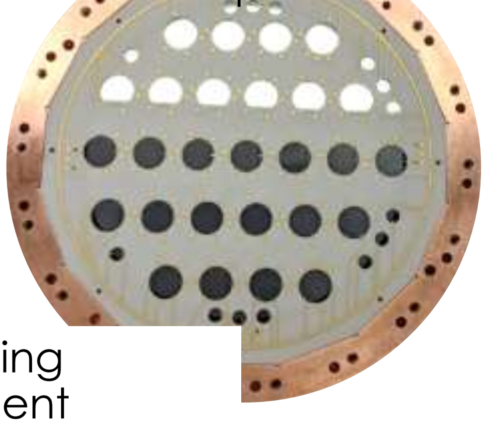
The Nab spectrometer, now installed at FNPB, will study kinematics of neutron decay particles: protons and electrons

Excellent agreement demonstrated in magnetic field

Precision magnetic mapping campaign nearly complete

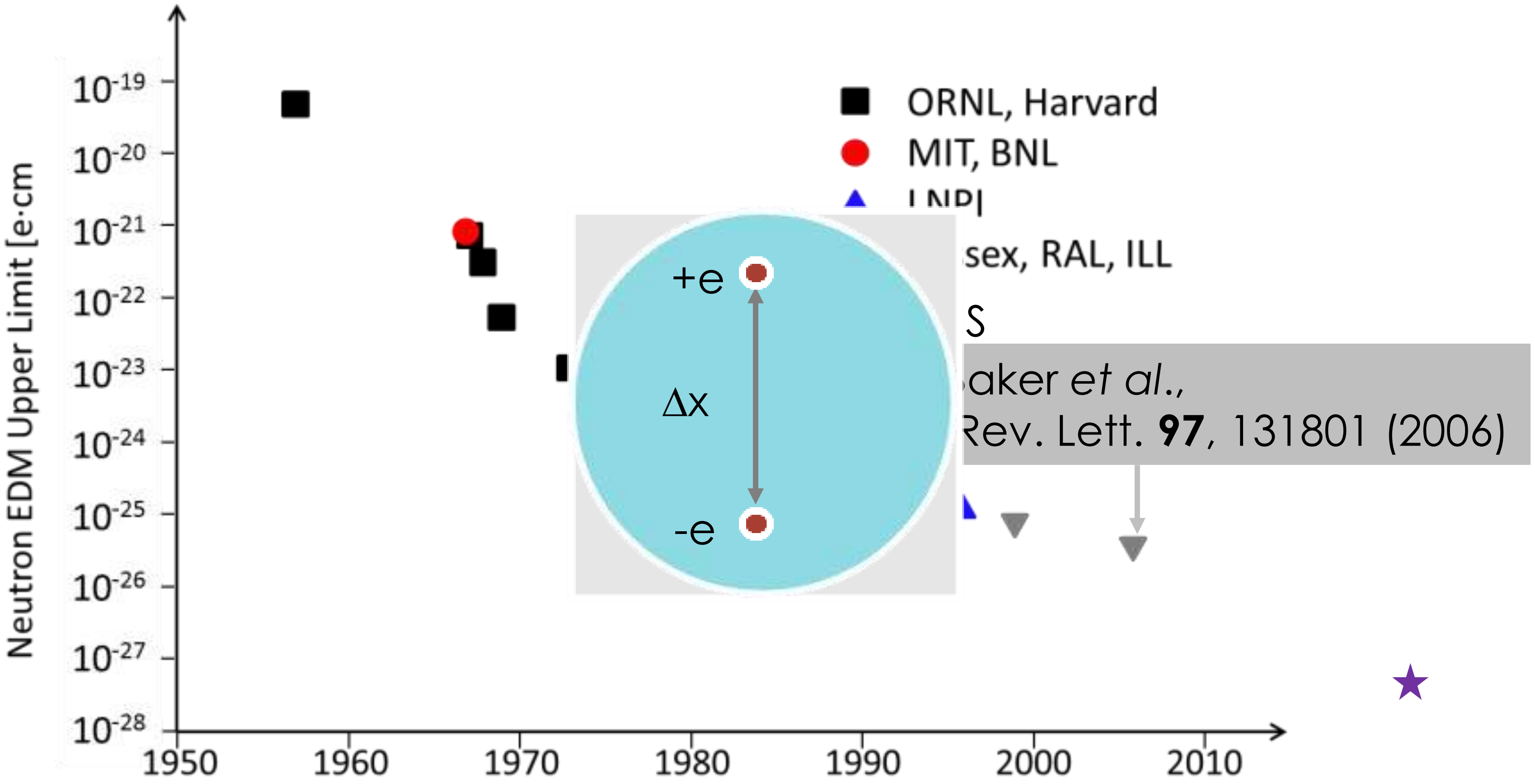


State of the art silicon detectors detect both electrons and protons



Acceptance testing underway: excellent performance so far!

Is The Neutron Round?



aker *et al.*,
Rev. Lett. **97**, 131801 (2006)

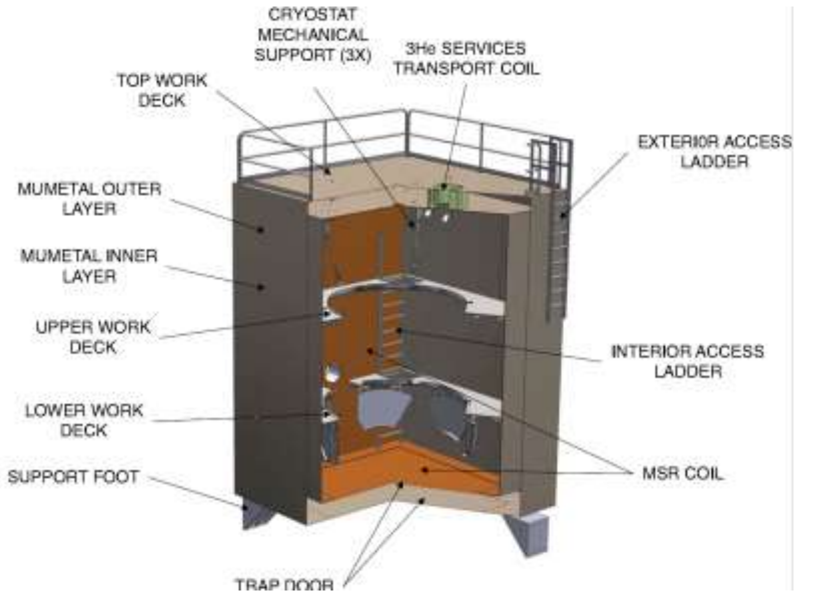
Current best limit: $|\mu_E| < 3 \times 10^{-26}$ e·cm
Our goal: $|\mu_E| < 2 \times 10^{-28}$ e·cm
SM prediction: ~ 10^{-32} e·cm (clean signature for new physics)

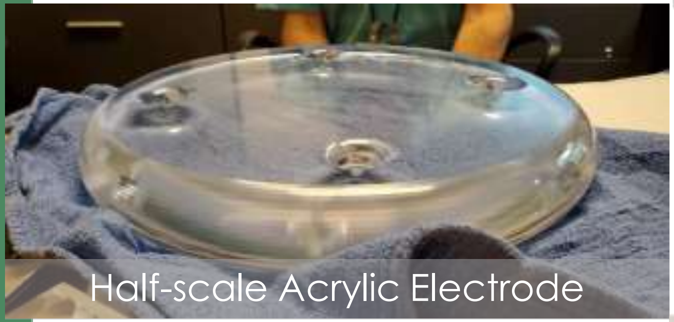
nEDM@SNS Status

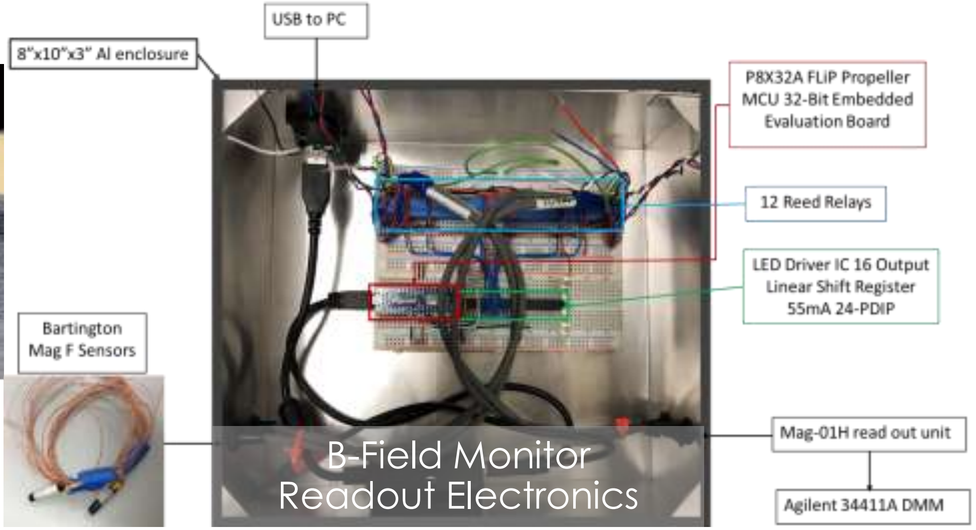

HV Electrode Test Apparatus


Spin Dressing Test Apparatus

Magnet Shield Room Out For Bid




Half-scale Acrylic Electrode


8"x10"x3" Al enclosure

USB to PC

P8X32A FLiP Propeller MCU 32-Bit Embedded Evaluation Board

12 Reed Relays

LED Driver IC 16 Output Linear Shift Register 55mA 24-PDIP

Bartington Mag F Sensors

Mag-01H read out unit

Agilent 34411A DMM

B-Field Monitor Readout Electronics


Magnet Coil Package

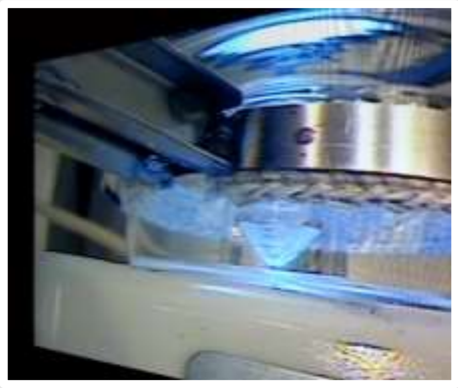
We have established a major Laboratory initiative in isotope R&D and production

Vision

- Lead the nation in isotope R&D, reactor-based production of radioisotopes, and enrichment of stable isotopes

Strategy

- Take advantage of expertise and unique capabilities to advance isotope science and deliver radioisotopes and stable isotopes
- Ensure continuing availability of isotopes to meet national needs



Science priorities

- Production of ^{252}Cf and other radioisotopes for industry and research, including superheavy element (SHE) discovery
- Development and production of medical isotopes
- Production of ^{238}Pu for space power applications
- Production of a variety of stable isotopes, using both electromagnetic separation and gas centrifuge technologies, at a new Stable Isotope Production Facility

Recent achievements

- Production of ^{96}Ru for RHIC experiments
- Development of ^{133}Ba production capability
- Chemical separation of high-purity ^{229}Th from ^{233}U
- Modified Building 4501 hot cells to support accelerator-based production of ^{225}Ac
- Delivering ^{227}Ac to Bayer
- Supporting international SHE discovery efforts

ORNL is now producing actinium-227 for Bayer

- Recovery and purification of radium-226 from legacy medical devices
- Irradiation of radium-226 feedstock in HFIR to produce actinium-227
- Chemical separation and purification of actinium-227
- Packaging and shipment to Bayer for extraction of radium-223 for cancer therapy

First sustained US production of enriched stable isotopes since 1983

Scientific motivation

- Beam Energy Scan program at the Relativistic Heavy Ion Collider (RHIC) identified a need for ^{96}Ru to explore the chiral magnetic effect in quark-gluon matter
  - Amount of ^{96}Ru remaining in DOE Stable Isotope inventory (~131 mg) was not sufficient to meet requirements

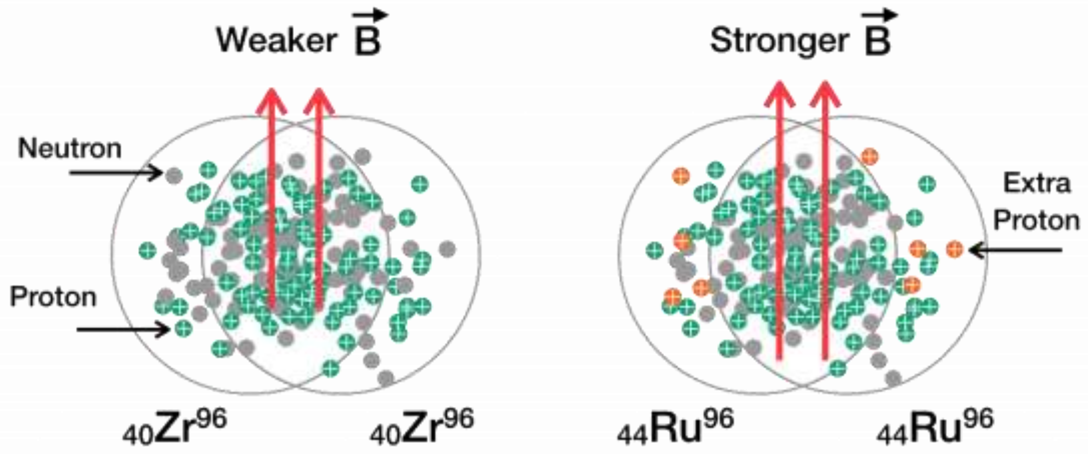


Image: Brookhaven National Laboratory

Our contribution

- The electromagnetic isotope separator (EMIS) at ORNL's Enriched Stable Isotope Prototype Plant was used **to produce ^{96}Ru,** enabling the shipment of 500 mg of this rare stable isotope to Brookhaven National Laboratory

Discussion