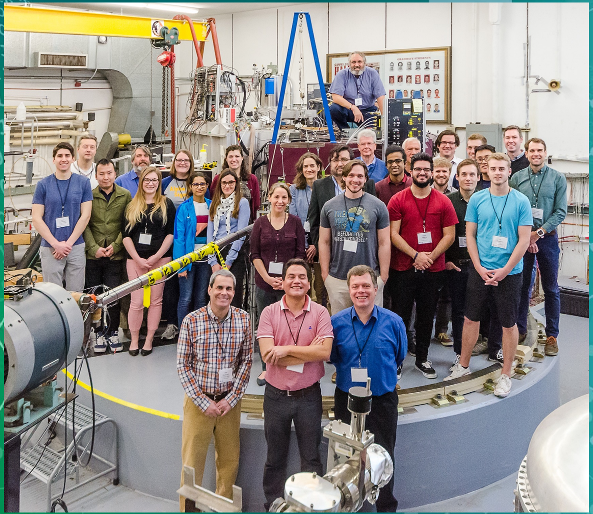
Oak Ridge National Laboratory

Tritium beams at FSU

Observables of interest for neutrinoless double beta decay

Alfredo Galindo-Uribarri

March 14-15, 2024



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

U.S. DEPARTMENT OF ENERGY

About me:


Norwegian Sea
Northwestern Passages
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Greenland
Iceland
Sweden
YT
NT
Finland
Norway
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Hudson Bay
AB
MB
United Kingdom
Denmark
BC
SK
NL
Ireland
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Mexico
Cuba
Puerto Rico
Mauritania
Mali
Niger
Chad
Sudan
Caribbean Sea
Nicaragua
Burkina Faso
Guinea

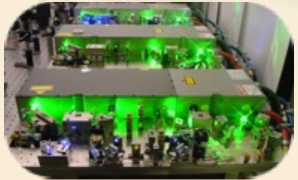
Content

- My timeline on the tritium project
- Double Beta Decay
    - Importance of tritium beams
- Efforts at other places
- Conclusions

Current interests

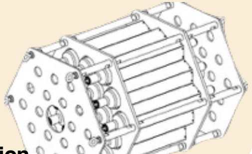
Isotope Program:
Stable and Radioactive-
New capabilities

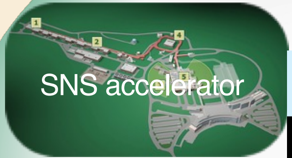
Ultra Sensitive
Analytical Techniques-
AMS
RIMS
NAA

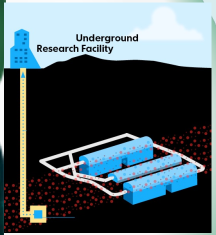


Quantum Information Science-
Machine Learning

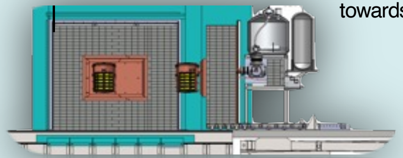
Modular Total Absorption Spectrometer (MTAS)-
β-decays of n-rich nuclei



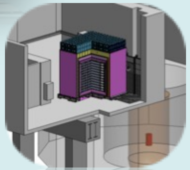




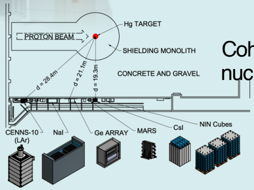
LEGEND-
towards 1 tonne ^{76}Ge experiment



PROSPECT-
A Precision Reactor Neutrino Oscillation and Spectrum Experiment at the 85MW HFIR



COHERENT-
Coherent elastic neutrino-nucleus scattering at SNS



Dark matter-
detectors technology

First Experiments with T in 1951 at Chalk River

Phys. Rev. 85 (1952)155

Protons and Deuterons from Li^6+T Reactions

T. P. PEPPER, K. W. ALLEN,* E. ALMQVIST, AND J. T. DEWAN†
Atomic Energy Project, National Research Council of Canada, Chalk River, Ontario, Canada
(Received November 9, 1951)

THE interaction of tritons with Li^6 may lead to the following exothermic reactions:[1]

$$Li^6+T=Li^7+D^2+0.988\text{ Mev} \quad (1)$$
$$Li^{7*}+D^2+0.509\text{ Mev} \quad (2)$$

THE REVIEW OF SCIENTIFIC INSTRUMENTS

Laboratory and Shop Notes

The Recovery and Purification of Tritium and He^3 Used in Ion Accelerators

K. W. ALLEN* AND E. ALMQVIST†
Physics Division, Atomic Energy of Canada, Ltd., Chalk River, Ontario, Canada
(Received June 25, 1952)

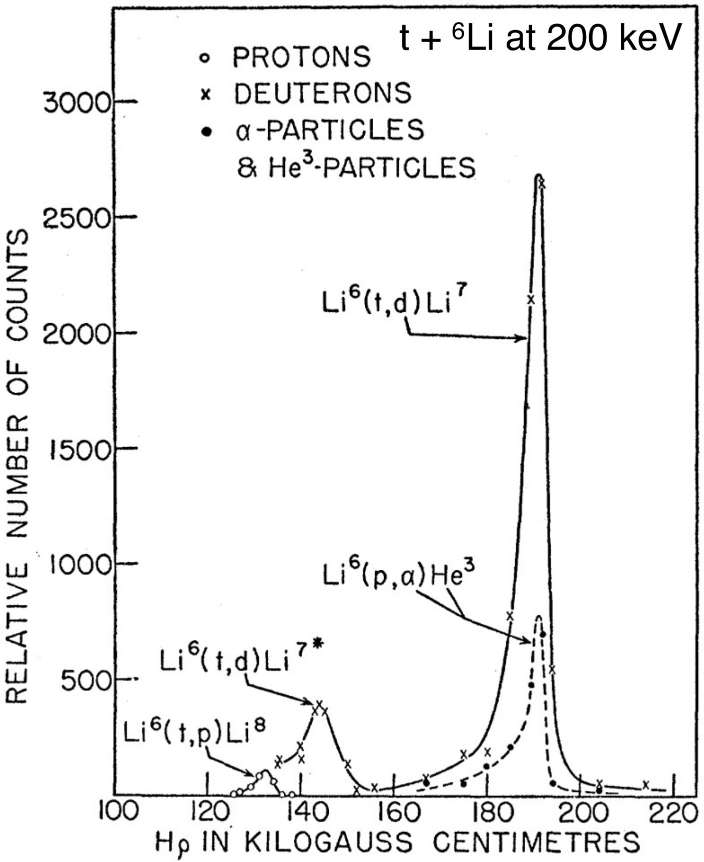


FIG. 2. Protons and deuterons from Li^6+T reactions observed at 90° to a 240-kev triton beam. The dashed curve represents He^3 and α-particles produced by 80-kev protons (HHH^+ ions) on Li^6. The relative intensities of the groups were obtained by correcting the areas under the peaks for variation of resolution of the magnet with $H\rho$.

2007 eRIBs'07 and 2009 HRIBF Workshop – needs of tritium beams

Exciting and cost-effective upgrade plans and the new mission

In November 2009 a very successful and internationally supported HRIBF users workshop was held: HRIBF, Upgrade for the FRIB Era in support of a proposed 70MeV cyclotron for HRIBF. The workshop was attended by 151 participants representing 44 institutions from 10 countries. The workshop identified exciting, cost-effective, and cost-saving upgrade plans that were submitted to DOE.

HRIBF, Upgrade for the FRIB Era
An HRIBF Users Workshop
November 13-14, 2009
http://www.phy.ornl.gov/workshops/users09/

eRIBs'07
International Workshop on
Electron Drivers for Radioactive Ion Beams
October 10th, 2007

Marriott Hotel and Conference Center
City Center, Newport News, Virgina

We urge you to consider the *outstanding scientific opportunities and societal applications* available though the facility, strategic relevance to FRIB, the importance of training nuclear scientists, and the proper use of recent investments – to find a way to preserve *unique capabilities* of HRIBF for science and the Nation.

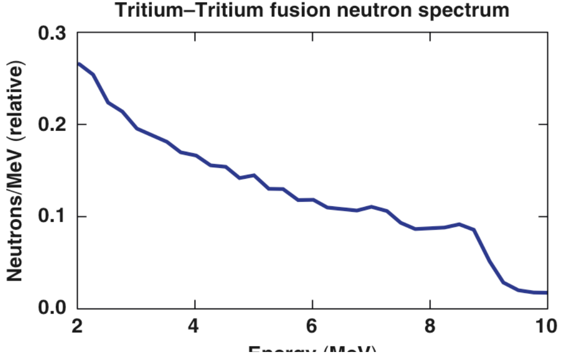
http://www.supporthribf.org/

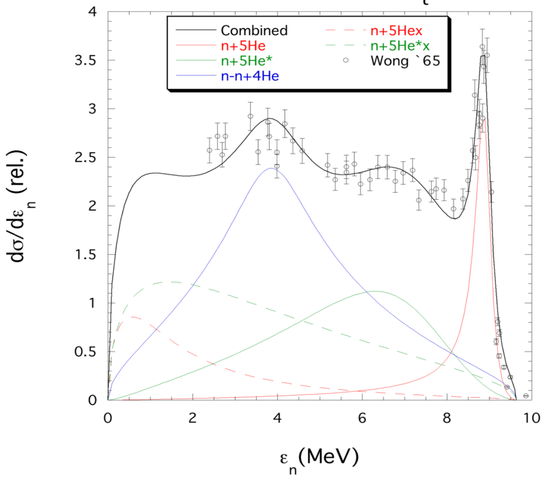
Over 200 U.S. and 400 International signatories as of March 2, noon

Tritium Beams
Applications Section

Alfredo Galindo-Uribarri,
Anna Hayes, Jutta Escher,
Mike Saltmarsch

2011 Letter of Support for a Tritium Beam Facility





Los Alamos
NATIONAL LABORATORY
EST.1943

Date: November 03, 2011

Subject:
National need for a tritium beam facility: an ideal opportunity at the ORNL Holifield Facility

To whom it may concern:

There are a significant number of nuclear reactions involving tritium that are crucial for Stockpile Stewardship, Nuclear Fusion, and Nuclear Astrophysics. For many of these, the cross sections and the distribution of reaction products are either unknown or uncertain. There are no tritium beam facilities in the United States to carryout these important measurements. The tandem accelerator at the Oak Ridge Holifield Radioactive Ion Beam Facility represents an ideal facility for producing the high quality tritium beams and making the measurements needed. Converting this tandem accelerator into a dedicated tritium beam facility would represent an exciting and timely opportunity for the nation.

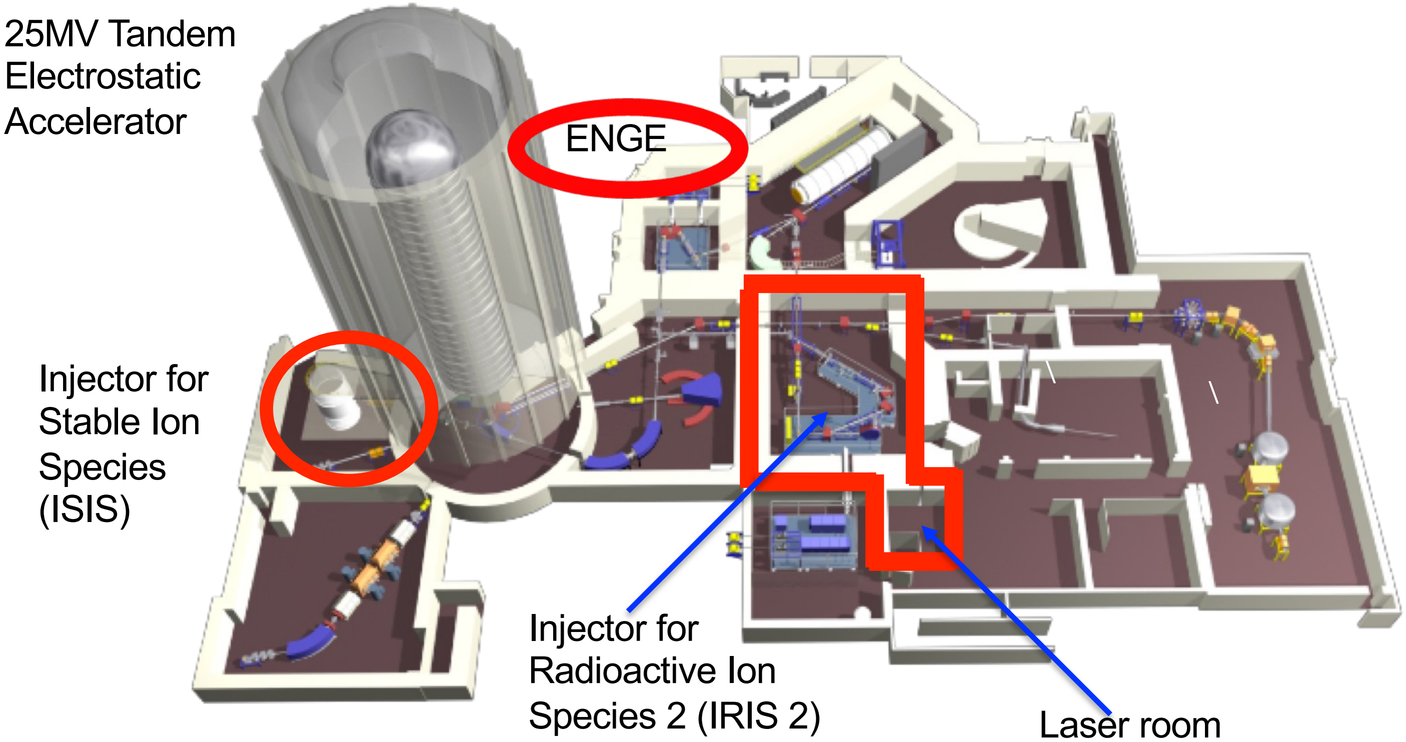
Measurements of the important tritium-tritium reactions are just one example of the type of experiments that would become accessible at such as facility. In burning systems undergoing tritium fusion, the high-energy gamma rays and neutrons produced in these reactions uniquely probe the plasma conditions. Measurements of the energy and angular distributions of these fusion products, as well as the reaction cross sections, would significantly enhance our ability to study the detailed physics of such thermonuclear systems. Many other unmeasured tritium reactions, including tritium on beryllium, lithium and carbon, have been shown in calculations to act as important diagnostics, including probing the effects of hydrodynamical instabilities and mixing on plasma properties. These and other unmeasured tritium-induced reactions also influence the nucleosynthesis of the light elements in the cosmos.

A national tritium beam facility would allow the basic and applied nuclear physics communities to address many of the remaining nuclear issues pertaining to burning of high-energy density plasmas. The creation of a high quality tritium beam at minimal cost, coupled with both the detection capabilities and the strong alliance with the academic community, makes Holifield the ideal facility for such an initiative.

Yours sincerely,

	Title
Joe Carlson	Group Leader & Lab Fellow, T-2
Mark Chadwick	Division Leader, XCP-DO
Stirling Colgate	Senior Lab Fellow, T-2
Steve Elliott	Technical Staff member, P-23
Jim Friar	Lab Fellow, T-2
Gerry Hale	Deputy Group Leader, T-2
Anna Hayes	Technical Staff member, T-2
Gerard Jungman	Technical Staff member, T-2
Bob Rundberg	Technical Staff member, C-NR
Jas Mercer-Smith	Lab Fellow, XDT-6
Stephen Sterbenz	Group Leader, XTD-3
Dave Vieira	Lab Affiliate, C-NR
Jerry Wilhelmy	Lab Fellow, C-NR

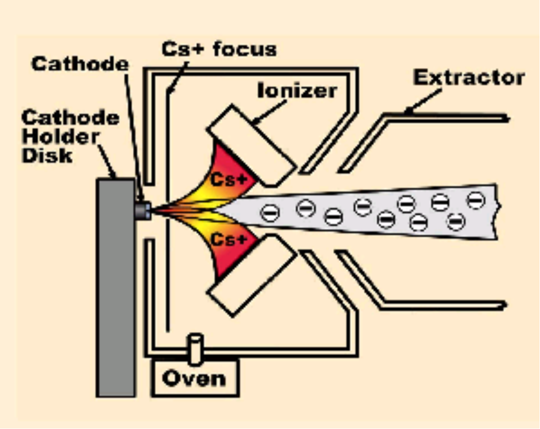
Holifield Radioactive Ion Beam Facility (HRIBF): Tritium beams, AMS and RIMS at ORNL



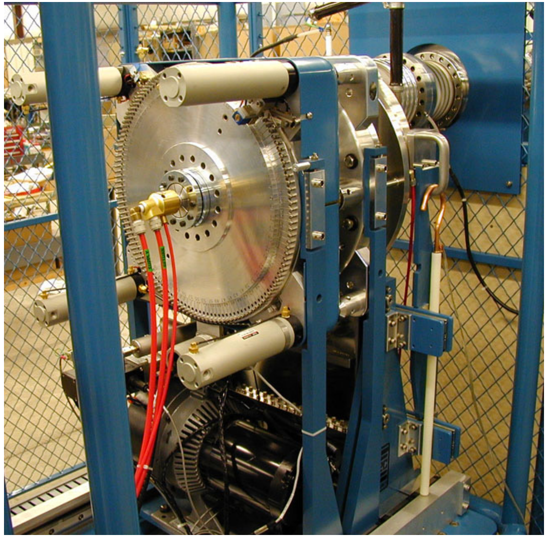
HRIBF shut down in 2012

NP Tools - Ion Sources

A typical sputter source heated Cs reservoir, an ionizer producing a focused Cs^+ beam at the sample, and an extraction electrode to accelerate and focus secondary negative ions from the sample into the injection beamline.



Important issues for AMS:
Memory effects
Multiple samples
High currents

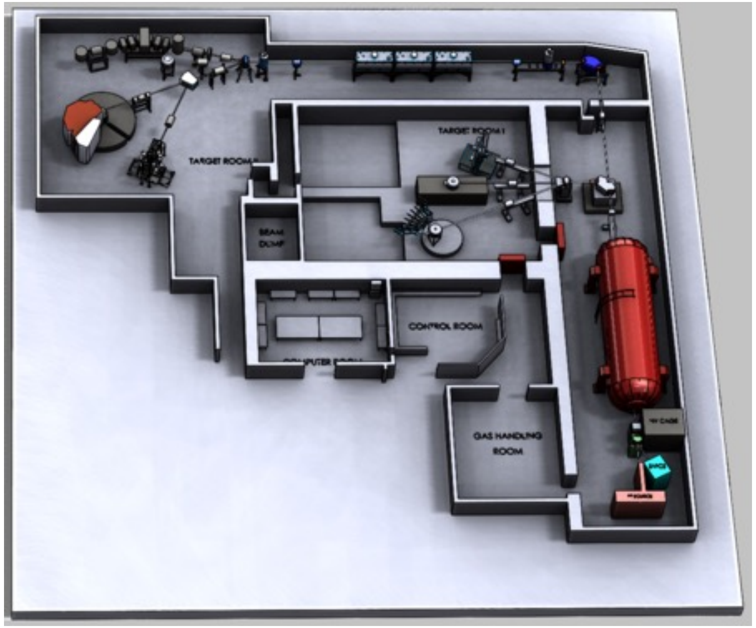


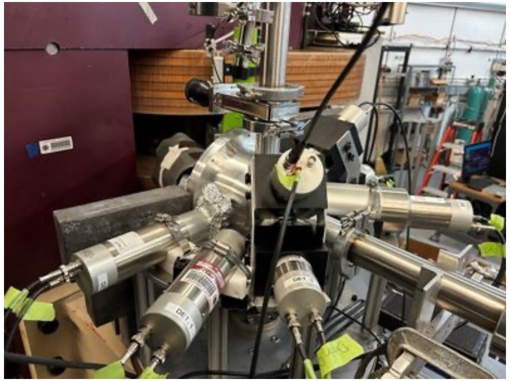
HRIBF at ORNL designated an historical site by APS
July 2016

Oak Ridge National Laboratory

2024 TRITON beams at FSU !!

- Availability of light ions (p, d, ^{3}He, ^{4}He, ^{3}H, …)
- Tandem + SC-LINAC for HE
- Super Enge Split-Pole Spectrograph
- Particle-Gamma detectors





Relationship

triton-induced reactions ⟷ reactions initiated by $A \leq 3$ projectiles

Charge exchange

(n, p)	(p,n)
$(d,2p)$	$(d,2n)$
$({}^3\mathrm{He}, 3p)$	$(t,3n)$
$(t, {}^3\mathrm{He})$	$({}^3\mathrm{He},t)$

One nucleon transfer

***p*-transfer**	***p*-pickup**
(d, n)	(n,d)
$({}^3\mathrm{He}, d)$	$(d,{}^3\mathrm{He})$
$(t,2n)$	(t, α)

***n*-transfer**	***n*-pickup**
(d, p)	(p,d)
(t, d)	(d, t)
$({}^3\mathrm{He},2p)$	$({}^3\mathrm{He}, \alpha)$

Two nucleon transfer

***d*-transfer**	**2*n*- , 2*p*-transfer**	
$({}^3\mathrm{He}, p)$	$({}^3\mathrm{He}, \mathrm{n})$	$(2p)$ "proton rich"
(t,n)	(t, p)	$(2n)$ "neutron rich"

Interest

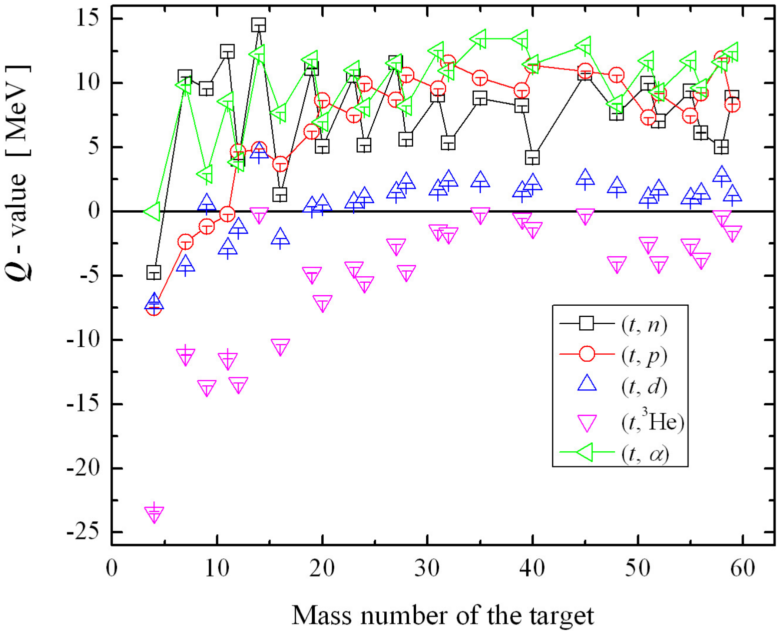
- Reactions with long lived radioactive targets
- Development of tritium targets
- t - scattering experiments (OMP)
- $(t, {}^{3}\mathrm{He})$ Charge Exchange
- $(t, p\gamma)$ as a surrogate reaction for (n, γ)
- $t\,(t, 2n)^{4}\mathrm{He}$ reaction studies for NIF
- Transfer reactions (t, p) compared with (p, t)
- Transfers with particle-gamma techniques?
- Polarization (?) $t + d_{pol}$
- Applications (plasma-materials interaction)

Transfer reactions

Reactions involving the transfer of one or more nucleons between beam and target nuclei have been a hugely useful source of nuclear structure information.

Transfer reactions were a trendy technique on the 70’s and 80’s.

For target nuclei between He and Ca as a function of target mass, **tritium-induced** transfer reactions are characterized by a relatively high *Q*-value.



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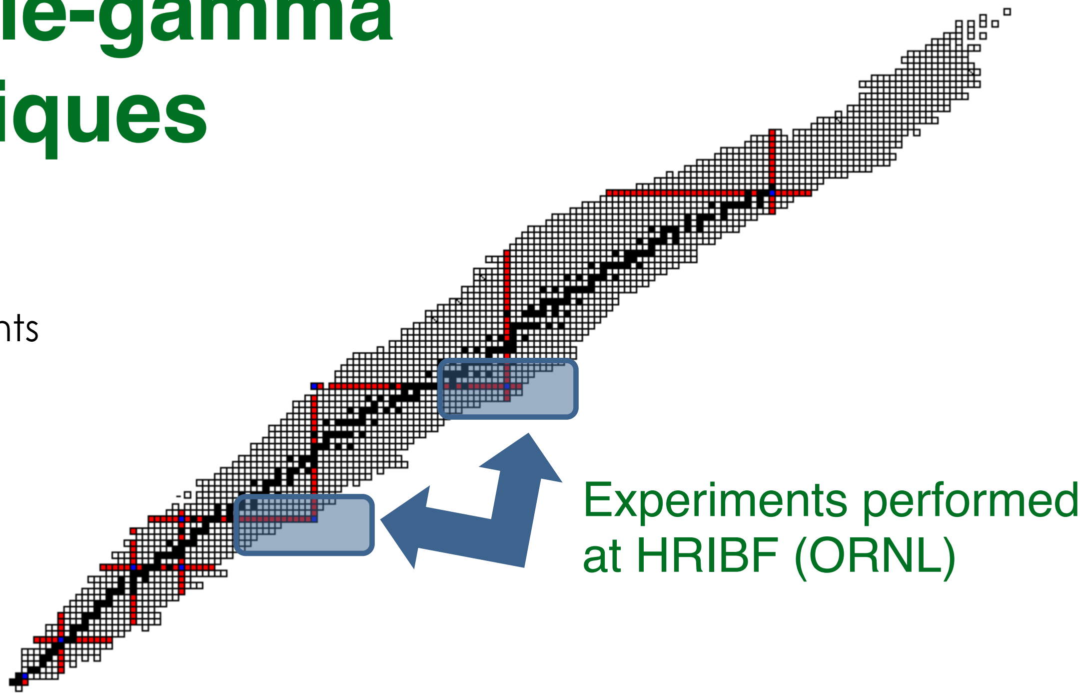
Particle-gamma techniques

B(E2) Measurements

Transfer Reactions

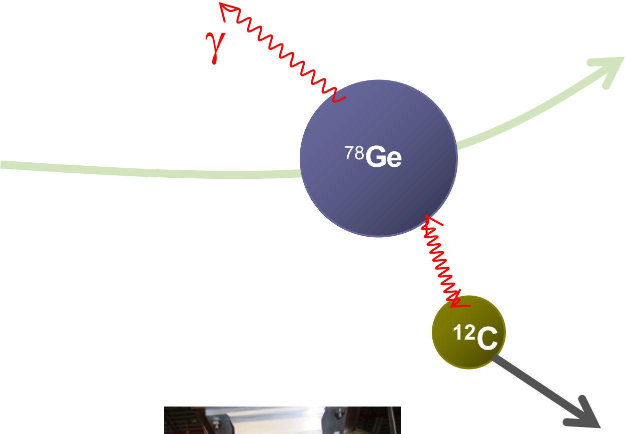


Collectivity of
Ge,Se,Te and Sn isotopes

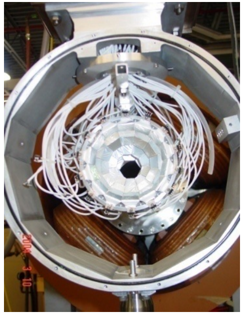
Coulex in Inverse kinematics with RIBs

Detected by a γ –ray spectrometer

Monitored using isobar separation techniques

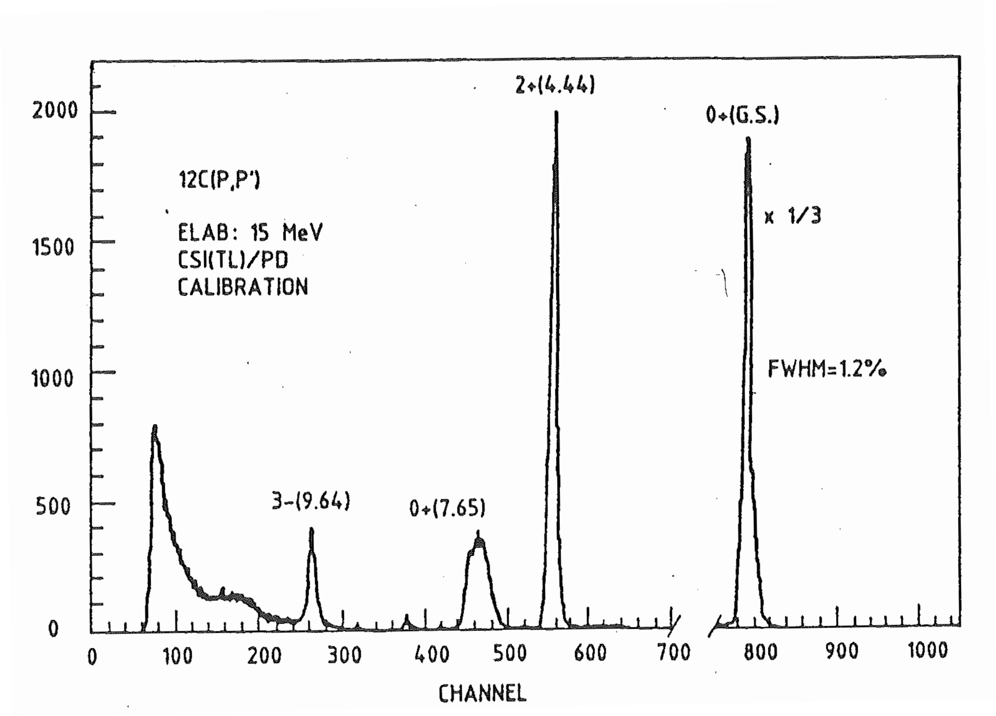


Detected by charged particle detector

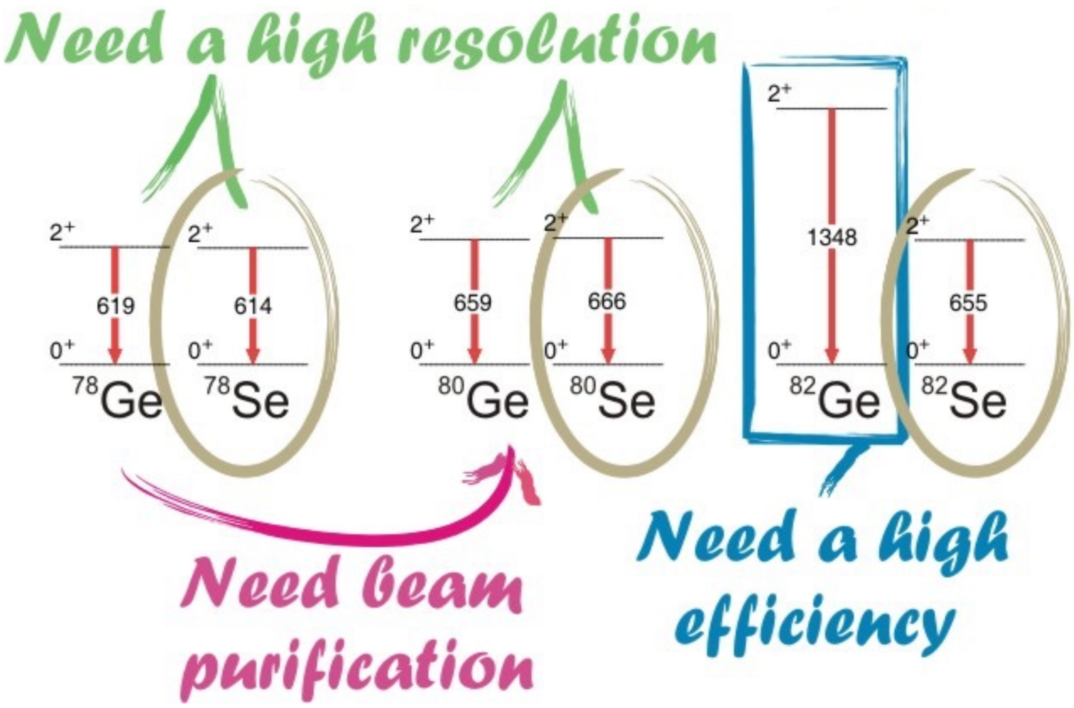


Bare Ball CsI(Tl) with PD readout
(to detect heavy recoils)
Minimum absorbers

CsI (Tl) response to 15 MeV protons



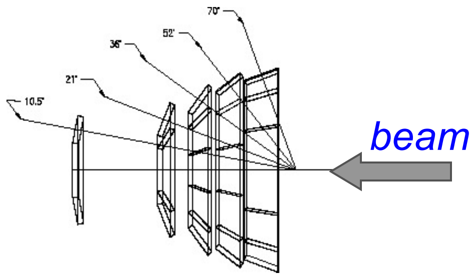
Challenges Ge isotopes

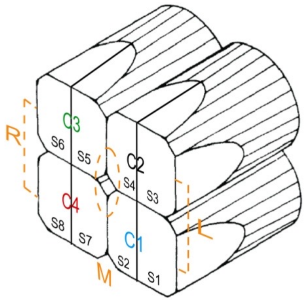


Doppler Broadening Correction

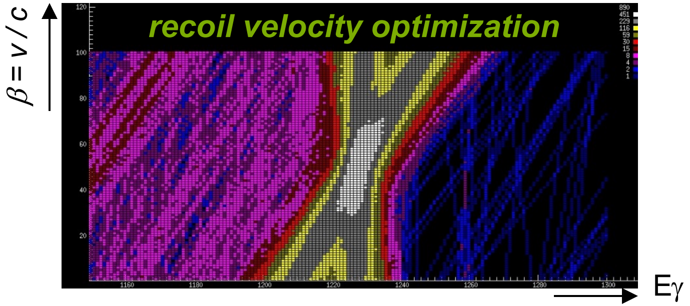
Use of both *recoil information* and *clover segmentation*

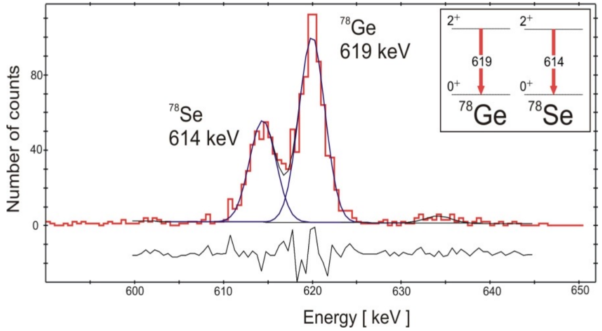
CsI
BareBall

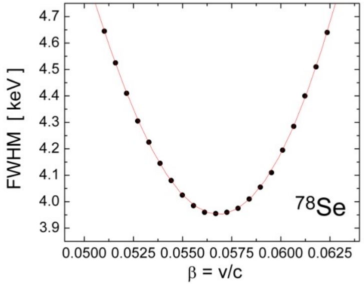




Clover Ge
Detectors







Correction for the Doppler broadening of the γ-rays was possible to **~ 3.9 keV FWHM** for 614 keV γ-ray i.e.

Energy resolution

0.63% FWHM

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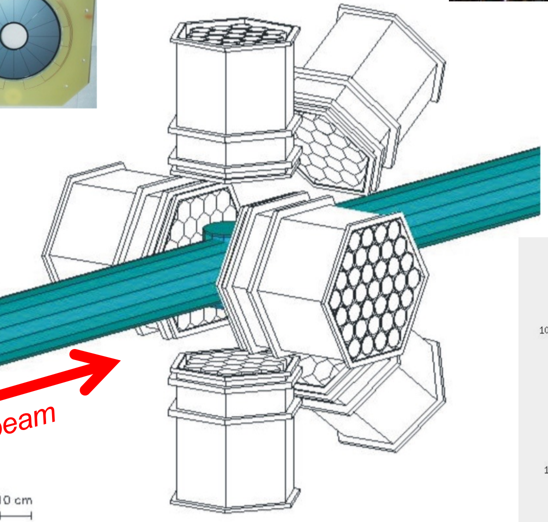
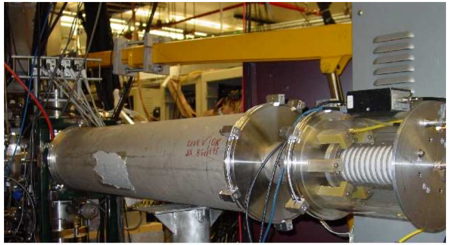
B(E2) ^{82}Ge

Si CD- like detector
S2-Type

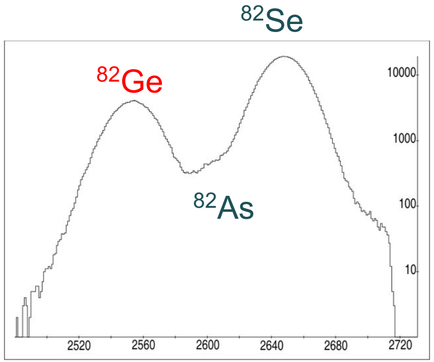


BaF$_2$
array

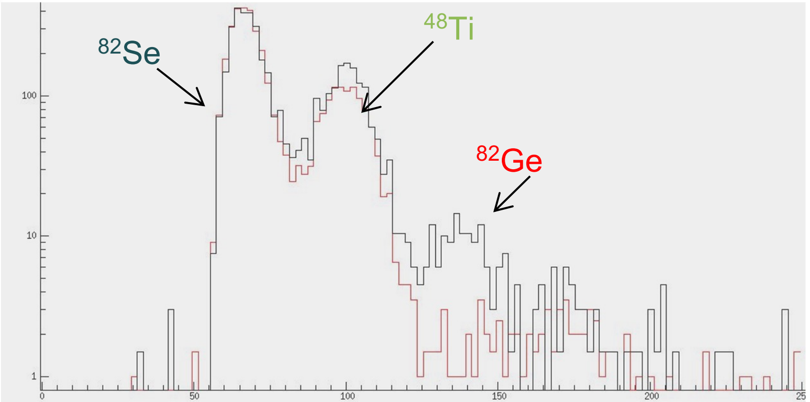
Bragg curve detector



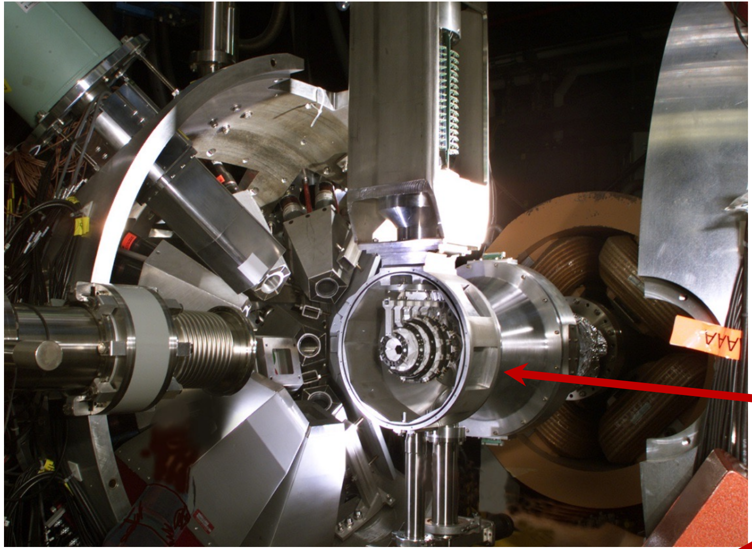
~22% of ^{82}Ge

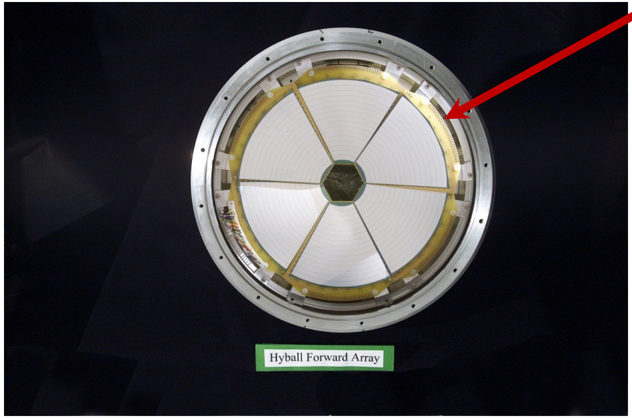


Range



RIB A=82 + 48Ti @ 220 MeV
82Se + 48Ti @ 220 MeV





HYBALL

HYBALL is a small, hybrid - 4π array of charged-particle detectors designed to be used with radioactive ion beams operating as an inner ball inside the CLARION array of CLOVER Ge detectors.

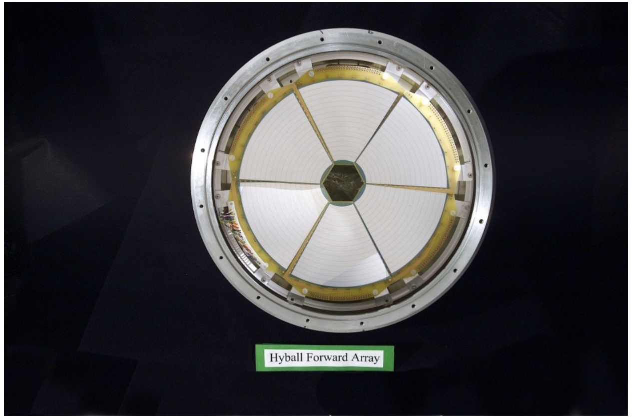
HYBALL consists of two parts:

a) a 95(79)-element CsI(Tl) array mounted in 9 concentric rings and

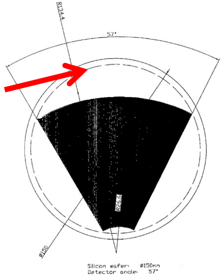
b) a forward array of double sided silicon strip detectors.
768 pixels
~500cm^2
The geometry of the chamber minimizes the exposure of the Ge detectors to the γ-rays and positrons resulting from the decay of the scattered radioactive ions.

Oak Ridge National Laboratory

ORNL Silicon ΔE-E Forward Array



6” ϕ Si technology



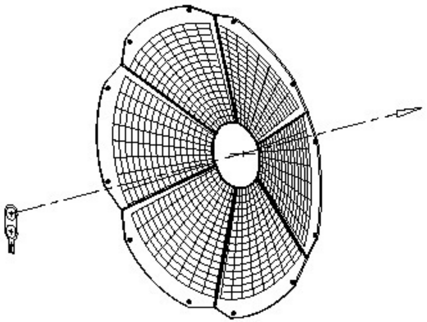
Cost effective

Good granularity

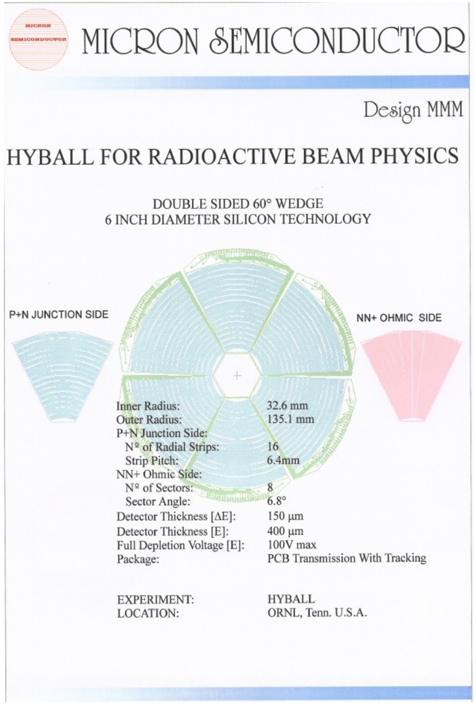
Large Efficiency

Modest-resolution

p-α discrimination in the Si achieved using only energy loss in a single layer of silicon (transmission mode) or energy loss-total energy (ΔE-E) in two layers of Si detectors (ΔE-E mode).



- **Ext. Diam. = 27.2 cm**
- **2 X 768 pixels**
- **16 axial strips**
- **8 radial strips**
- **DE 150 mm**
- **E 400 mm**
- **Custom electronics**
- **Also used by TIARA**



MICRON SEMICONDUCTOR

Design MMM

HYBALL FOR RADIOACTIVE BEAM PHYSICS

DOUBLE SIDED 60° WEDGE
6 INCH DIAMETER SILICON TECHNOLOGY

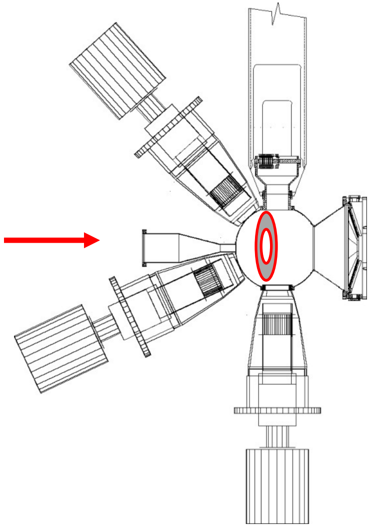
P+N JUNCTION SIDE

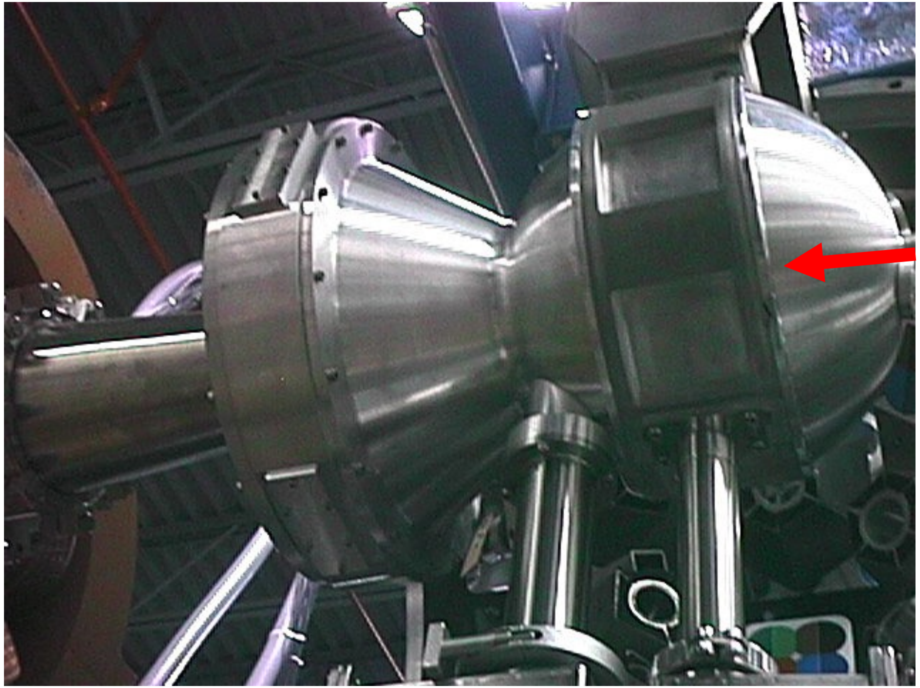
NN+ OHMIC SIDE

Inner Radius:	32.6 mm
Outer Radius:	135.1 mm
P+N Junction Side:	
N° of Radial Strips:	16
Strip Pitch:	6.4mm
NN+ Ohmic Side:	
N° of Sectors:	8
Sector Angle:	6.8°
Detector Thickness [ΔE]:	150 μm
Detector Thickness [E]:	400 μm
Full Depletion Voltage [E]:	100V max
Package:	PCB Transmission With Tracking
EXPERIMENT:	HYBALL
LOCATION:	ORNL, Tenn. U.S.A.

HYBALL CHAMBER

The geometry of the chamber minimizes the exposure of the Ge detectors to the γ–rays and positrons resulting from the decay of the scattered radioactive ions.



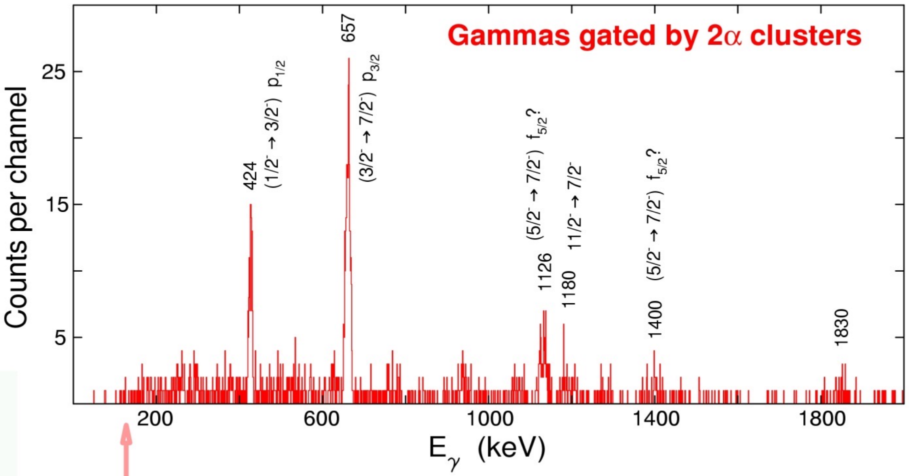


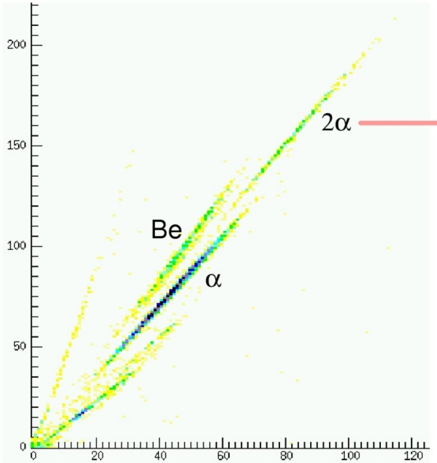
Transfer Reactions using particle-gamma techniques

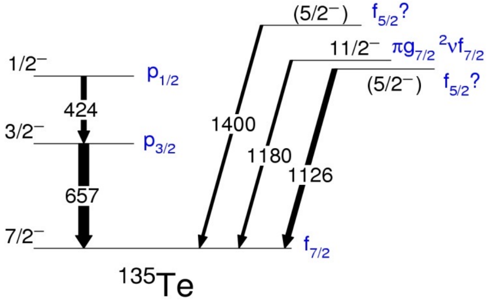
^{9}Be(^{134}Te,^{8}Be)^{135}Te

↳ 2α

~4 MeV per nucleon







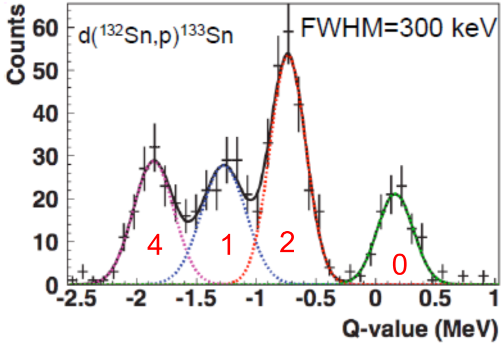
Transfer Reactions

A Si Detector: ORRUBA + SIDAR

133Sn

5 known levels [ENSDF] in first 2 MeV of excitation energy

Si array



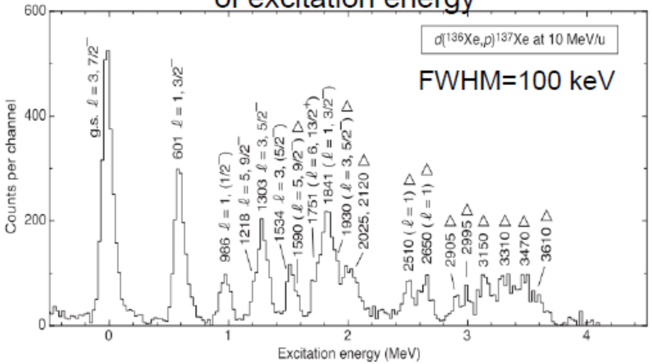
K. L. Jones et al., Nature (London) 465, 454 (2010).

A Solenoidal Spectrometer: HELIOS

137Xe

27 known levels [ENSDF] in first 2 MeV of excitation energy

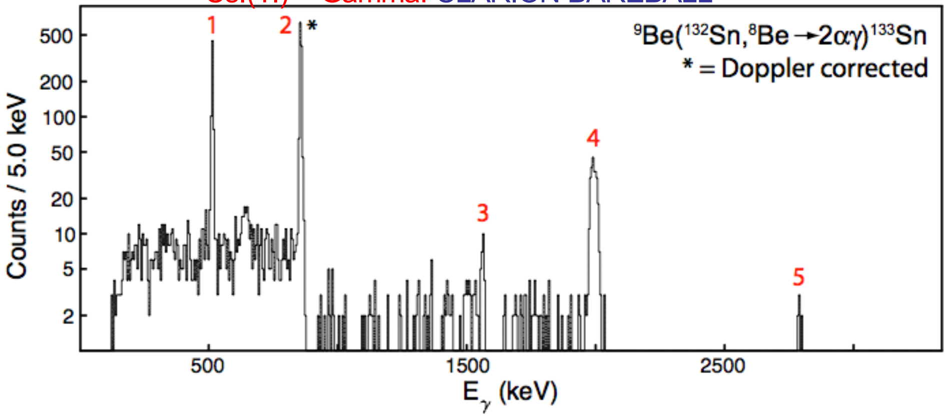
Solenoid



B.P. Kay et al., Phys. Rev. C 84, 024325 (2011).

CsI(Tl) + Gamma: CLARION BAREBALL

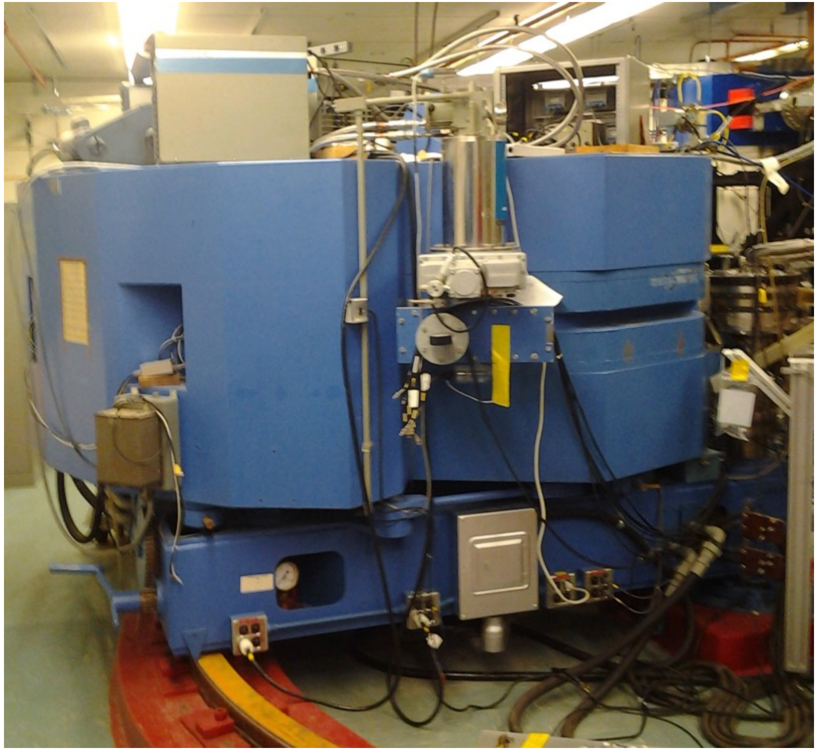
Particle-gamma techniques



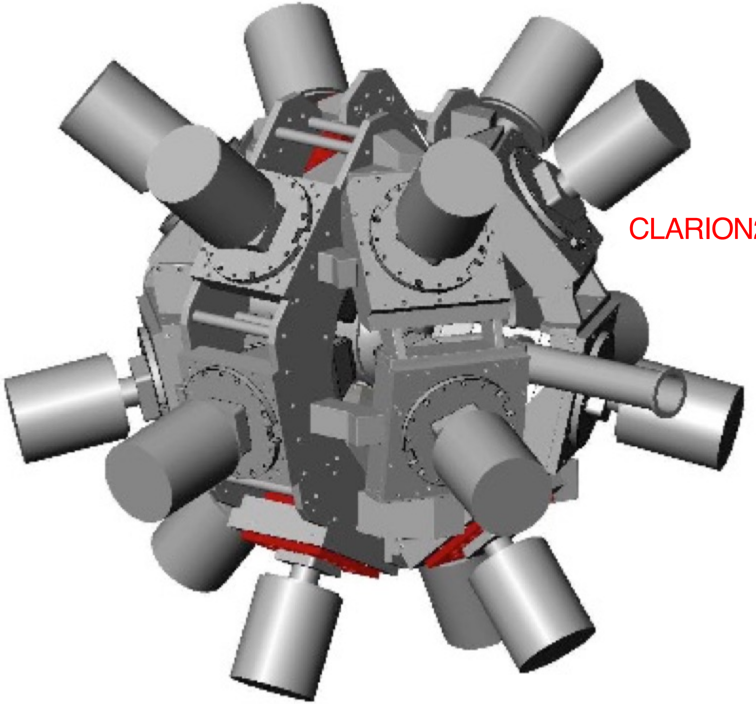
^{132}Sn n Transfer

Complete Tritium Beam Measurements

Particle singles
(Absolute Cross Sections, Low E_x, low level density)



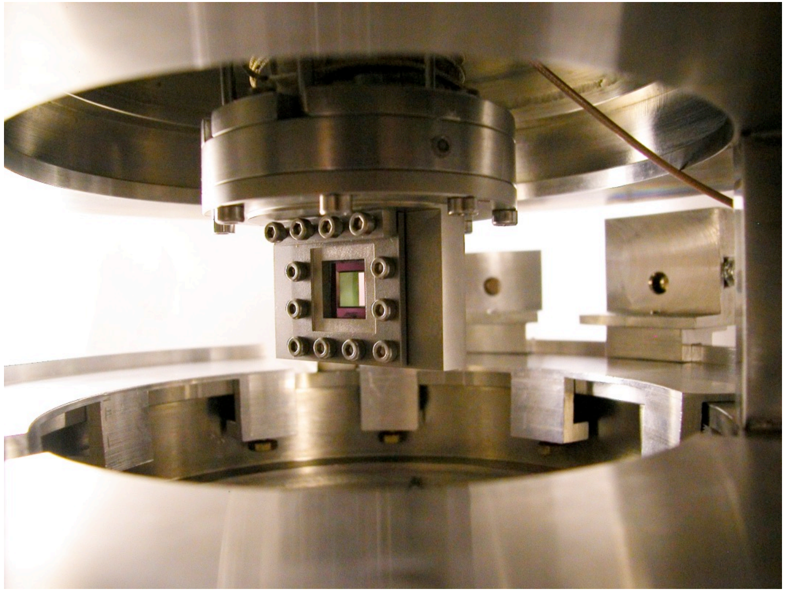
Particle-γ
(relative Cross Sections*, high E_x, high level density)



*normalized to absolute values from magnetic spectrometer data at low E_x

Polarized H and D target

- Dynamic Nuclear Polarization Technique
- Polystyrene foil, thickness ~ 0.1 - 20 mg/cm^2
- Low temperatures : T = 225 mK ,
- High Magnetic Fields : B = 2.5 T



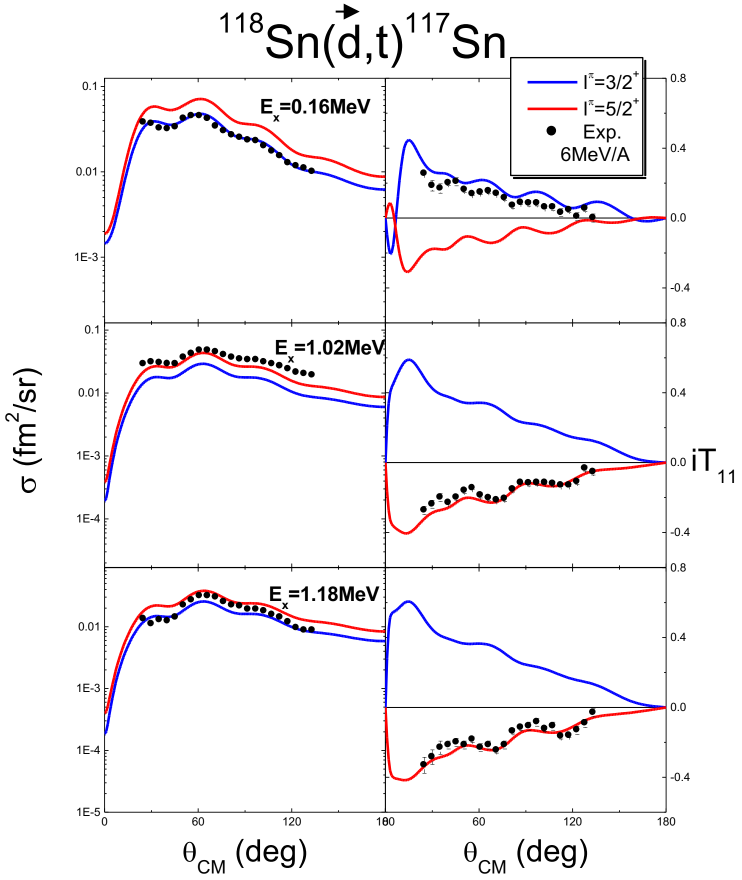
J.P. Urrego-Blanco, Ph.D. UTK

Target is contained in a superfluid helium leak tight cell with 500 nm thick Si_3N_4 windows

Polarization is sampled in real time with an NMR coil attached to the target

Proof of principle performed at PSI (Switzerland) using elastic scattering $\vec{p}(^{12}\mathrm{C},^{12}\mathrm{C})p$ at 38 MeV https://doi.org/10.1016/j.nimb.2007.04.257

Transfer Reactions and polarization



$$\frac{[\,i\,T_{11}\,(\theta)\,]_{j=l+1/2}}{[\,i\,T_{11}(\theta)\,]_{j=l-1/2}} = -\frac{l}{l+1}$$

- ✓ Spectroscopic tool for the *j*-assignment of single particle states
- ✓ Information on the spin-orbit interaction
- ✓ Sensitivity of the analyzing power increases at low energies

https://doi.org/10.1016/0375-9474(75)90121-9

The study of 0νββ decay

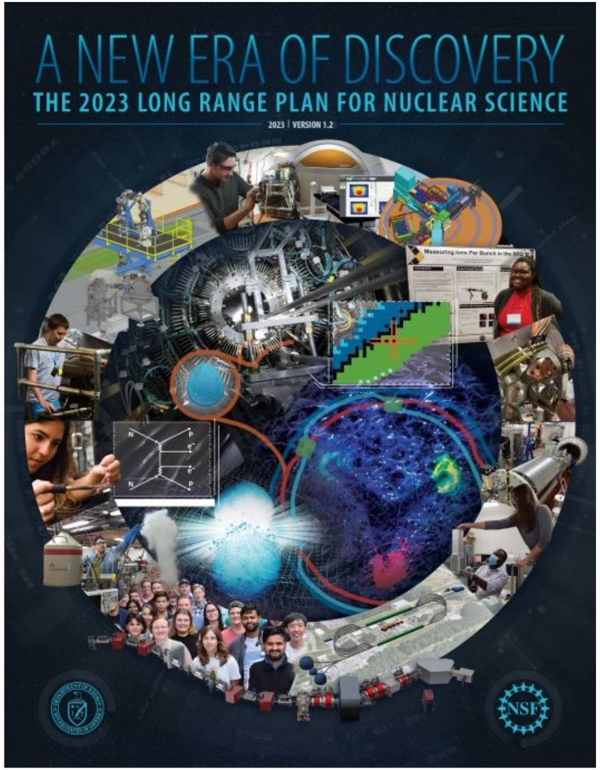
Is the ***most sensitive test*** of the existence of Majorana neutrino.

0νββ decay experiments are the ***most important*** present-day underground physics ***experiments*** (LRP 2023).

Observation of 0νββ decay would be equivalent to uncovering ***new physics*** beyond the standard theory.

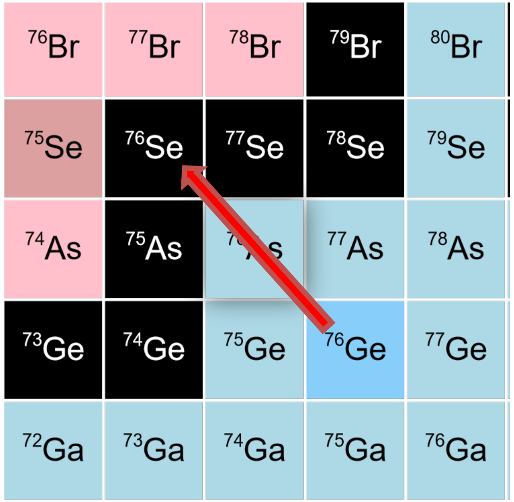
Reliable calculation of NME are ***decisive***.

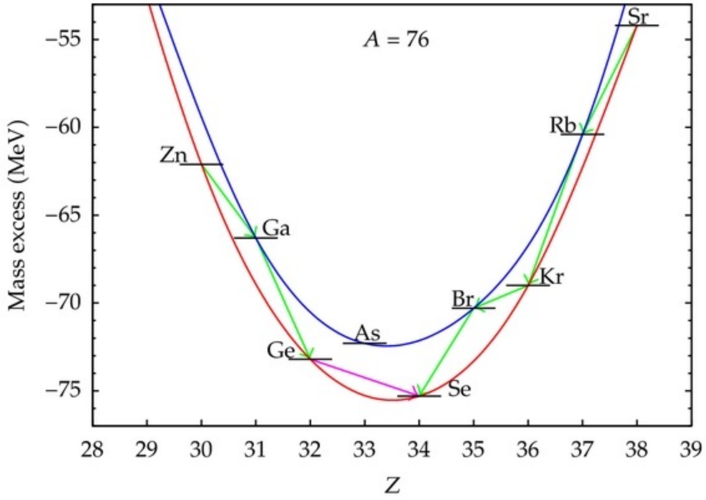
https://doi.org/10.1007/978-3-642-46648-9



Double β-decay

$$^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z-2}Y_{N+2} + 2e^{-} + (2\bar{\nu})$$





- ✓ Process mediated by the weak interaction occurring in even-even nuclei where the single β-decay is energetically forbidden

- ✓ The role of the pairing force

Neutrinoless Double Beta Decay

The 0νββ decay rate is typically expressed as the product of three main factors:

$$T^{0\nu} = g_A^4 \times G^{0\nu} \times |\, m^{\text{eff}} \,|^2 \times |\, M^{0\nu} \,|^2$$

i. a phase-space factor, describing the motion of the electrons;
ii. a term that can be expressed in terms of the effective neutrino mass, containing information about the emission and reabsorption of neutrinos;
iii. the square of a nuclear matrix element (NME) connecting the initial and final nuclear states, including intermediate configurations and g.s. correlations.

It's crucial to have confidence in the reliability with which the NMEs can be calculated.

Nuclear structure experimental information and g.s. correlations are essential for a proper description.

Nuclear Matrix Element (NME)

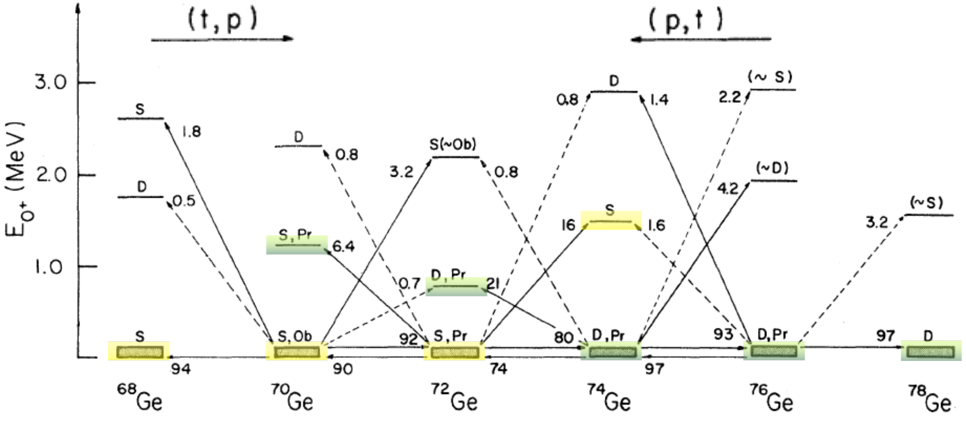
$$\left|M_{\varepsilon}^{\beta\beta 0\nu}\right|^2 = \left|\left\langle \Psi_f \left| \hat{O}_{\varepsilon}^{\beta\beta 0\nu} \right| \Psi_i \right\rangle\right|^2$$

✓ Calculations (still sizeable uncertainties): QRPA, Large scale shell model, IBM, EDF …..

✓ Measurements (useful for 0νββ):
(π^+, π^-)
single charge exchange (^{3}He,t), (d,^{2}He)
electron capture
transfer reactions
muon capture
heavy-ion double charge-exchange (DCE)

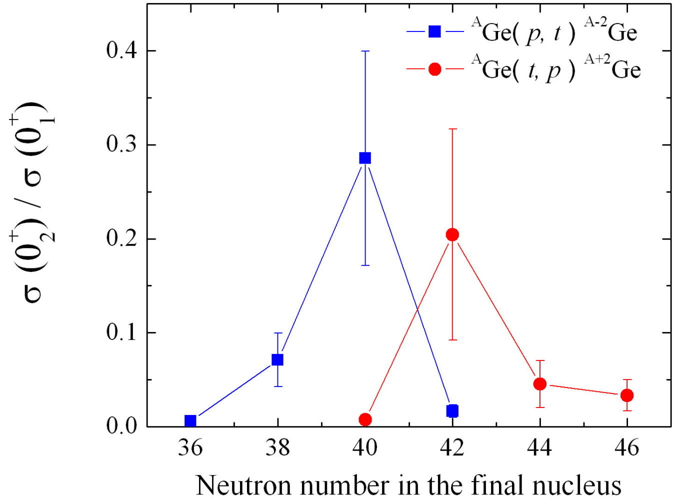
Nuclear structure of germanium isotopes

Two neutron transfer reactions assesses the existence of shape transitions and shape coexistence in the even-*A* germanium nuclei



https://doi.org/10.1103/PhysRevC.25.2812

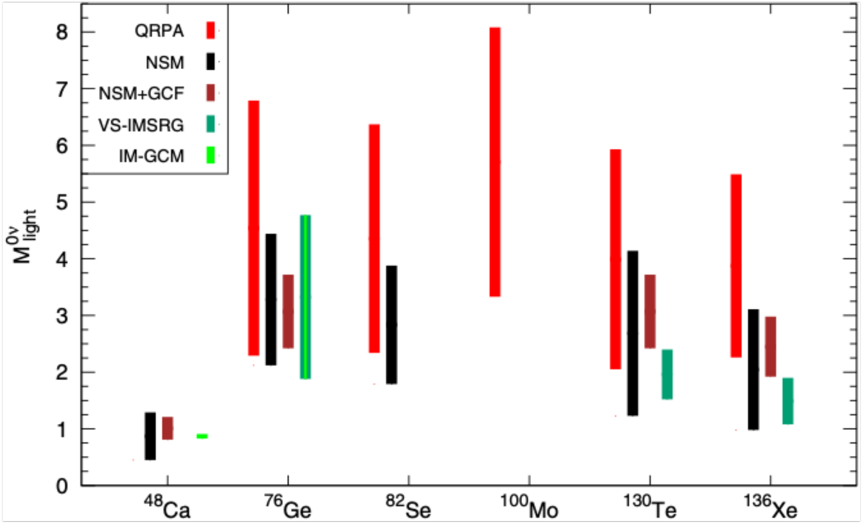
Phys. Lett. 72B (1978) 447-449



Transition strength between states with ***similar*** (***different***) nature is ***favored*** (***unfavored***)

0νββ-decay NME from nuclear theory : 2023

https://doi.org/10.1007/s40766-023-00049-2



Modern calculations suggest relatively ***smaller NME*** values by including:

- short-range correlations (**J. Holt** talk),
- normal-ordered two-nucleon currents,
- EFT for β decay.

QRPA: Quasiparticle Random Phase Approximation. https://doi.org/10.1103/PhysRevC.107.044305
NSM: Nuclear Shell Model https://doi.org/10.1103/PhysRevC.107.044305
NSM-GCF: NSM complemented with the Generalized Contact Formalism. https://doi.org/10.1103/PhysRevC.106.065501
VS-IMSRG: Valence-Space In-Medium Similarity Renormalization Group https://doi.org/10.48550/arXiv.2307.15156
IM-GCM: In-Medium Generalized Coordinate Method https://doi.org/10.1103/PhysRevLett.127.242502

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Future Joint Experimental Effort to measure observables relevant to 0vbb ?

Goal: establish a broad experimental effort attracting an international team to measure the observables that could have the maximum impact to constraint the 0vbb NME's and to validate the leading theoretical predictions.

The measurements include those made with tritium beams at FSU such as (t,p) reactions but also other transfer reactions at FSU or elsewhere (Osaka/Grand Raiden)

Other possibilities include charge exchange reactions and muon capture PSI, JPARC and TRIUMF (?). Heavy ions (NUMEN)

Other observables. Correlations with B(E2)s (work of J. Menendez)

Double Charge Exchange

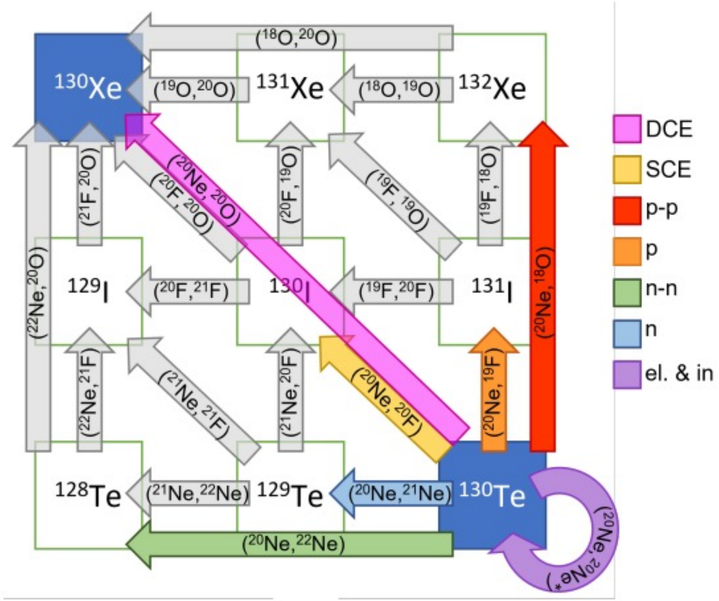
Over the last few years, major interest has raised for heavy-ion induced Double Charge-Exchange (DCE) studies, especially because of their possible connection to $0\nu\beta\beta$ decay.

Exploratory studies have been started at RIKEN in Tokyo and at RCNP in Osaka (Matsubara et al., 2013; Kisamori et al., 2016; Takahisa et al., 2017).

An intense activity is also being pursued at the Istituto Nazionale di Fisica Nucleare–Laboratori Nazionali del Sud (INFN-LNS) in Catania, in the frame of the NUMEN project.

A new DCE reaction, the (^{20}Ne,^{20}O), has been recently studied for the first time, looking for $\beta^-\beta^-$-like transitions. In addition, important results have been achieved on the β+β+ side by the renewed use of the (^{18}O,^{18}Ne) reaction in upgraded experimental conditions.

NUMEN



Network of possible nuclear reaction routes connecting initial and final states in the 20Ne+130Te DCE reaction.

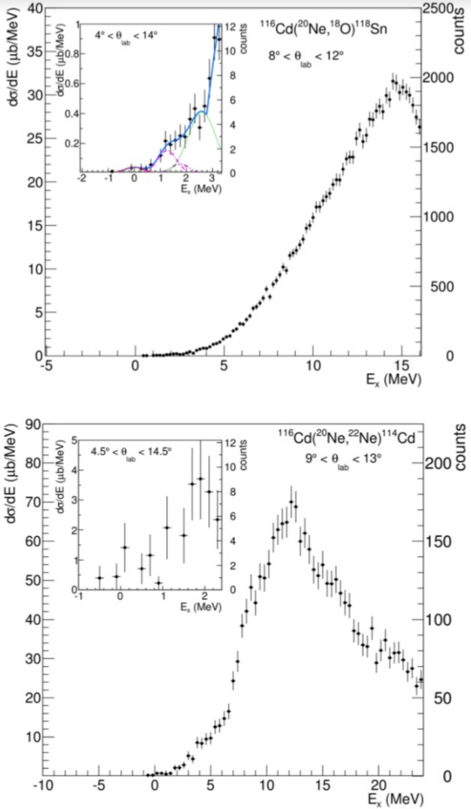


Figure 1. Upper panel: excitation energy spectra of the ^{116}Cd(^{20}Ne,^{18}O)^{118}Sn two-proton transfer reaction at 306 MeV and 8° < θ_{lab} < 12°. Inset: zoomed view of the low-lying states for 4° < θ_{lab} < 14°. Lines obtained from best-fit procedures identify transitions to particular states: ground state (0$^+$) (red dashed-line), 1.229 MeV (2$^+$) (magenta dashed-dotted line), 1.758 MeV (0$^+$) (violet dashed-double-dotted line), a mixture of states between 2 and 3 MeV (green dotted-line) and the global result (blue line) that includes a background curve for the high level density above ~ 3 MeV. Lower panel: excitation energy spectra of the ^{116}Cd(^{20}Ne,^{22}Ne)^{114}Cd two-neutron transfer reaction at 306 MeV and 9° < θ_{lab} < 13°. Inset: zoomed view of the low-lying states for 4.5° < θ_{lab} < 14.5°.

Oak Ridge National Laboratory

Conclusion

Exciting times to come!
Identify best strategy by critical assessment of previous transfer measurements
Need Theoretical Guidance