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U.S. DEPARTMENT OF ENERGY | Office of Science

Studying the structure of the A=98 decay products – a path to detailed decay spectroscopy experiments

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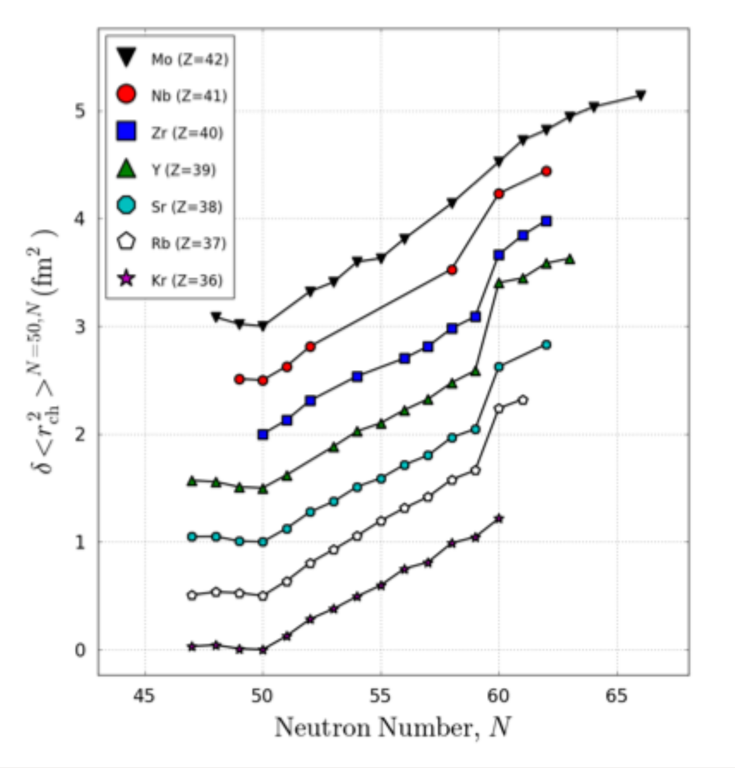
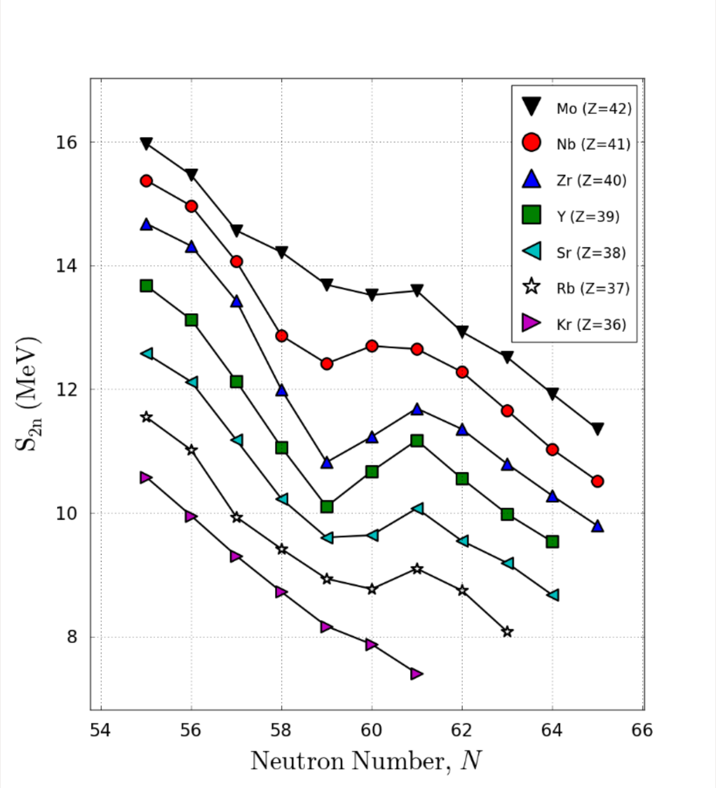
Tennessee Tech. University

Shape coexistence in A=100 region

- Region characterised by sudden onset of deformation at N = 60.
- Well investigated by laser spectroscopy for charge radii (left) and penning trap measurements for 2-n separation energies (right)



T. J. Procter et. al, Eur.Phys.J. A 51, 23 (2015)



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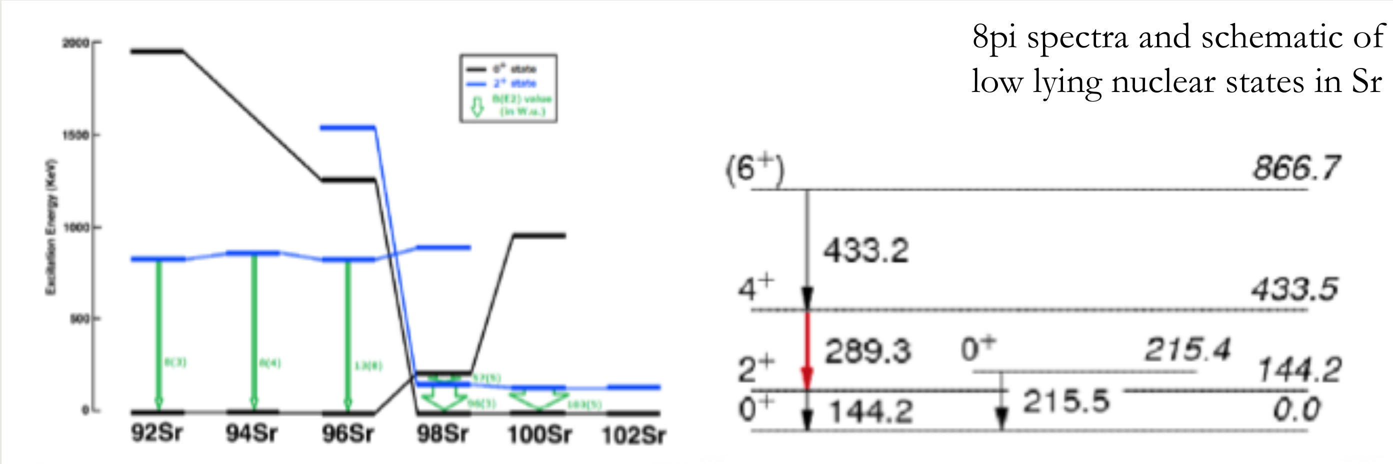
Shape coexistence in A=100 region

- A = 100 region characterised by strong E0 transitions between low lying 0^+ states.
- Large interest in ^{98}Sr due to display of different nuclear shapes coexisting at similar energies.

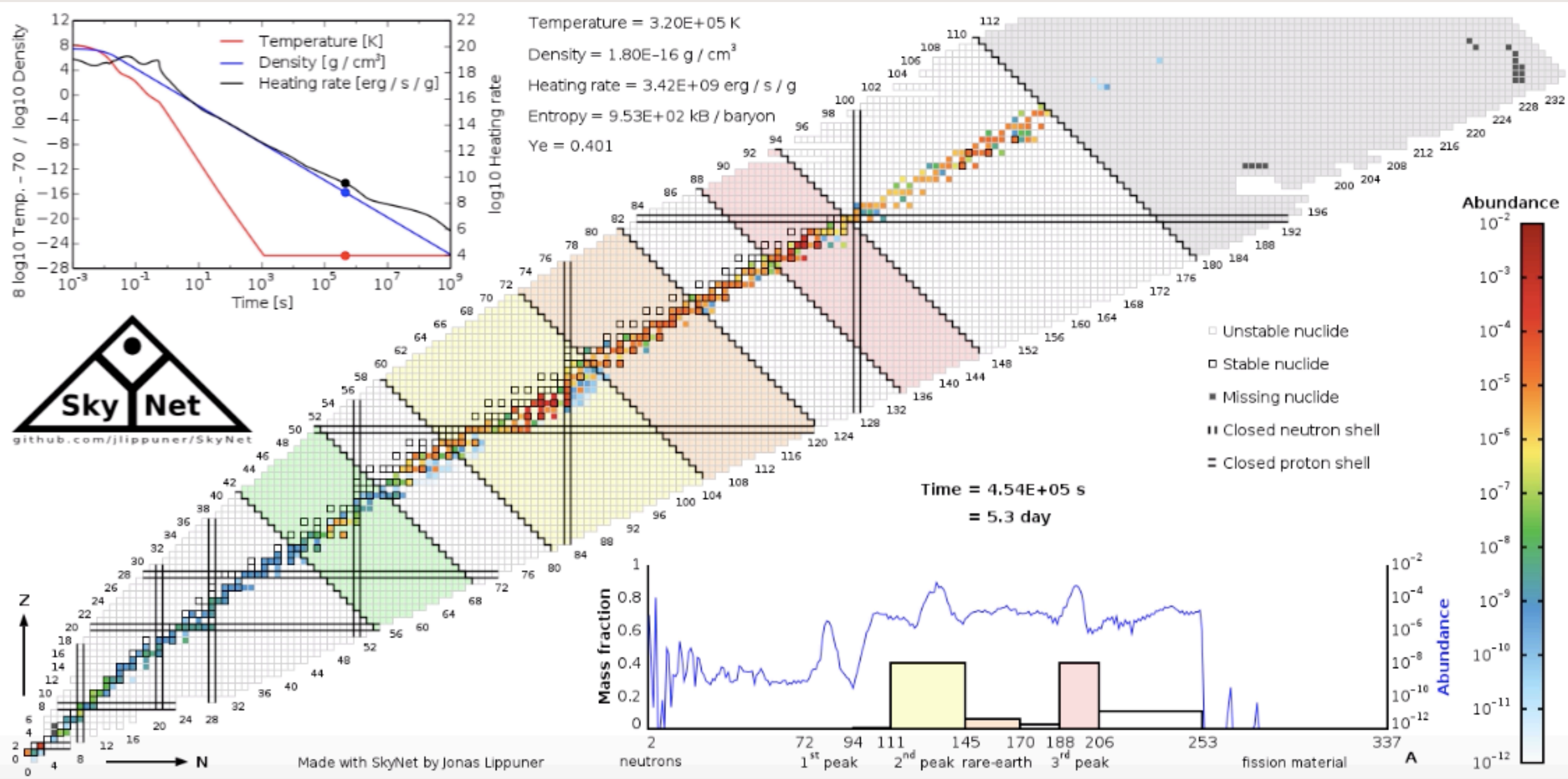


8pi spectra and schematic of low lying nuclear states in Sr

- Large deformations of nuclei within this region (around N=60) allow for isomerism due to K hindrance.
- Recent work on the levels of ^{98}Sr populated by decay from ^{98}Rb shows the presence of these isomers that appear in the nanosecond range.

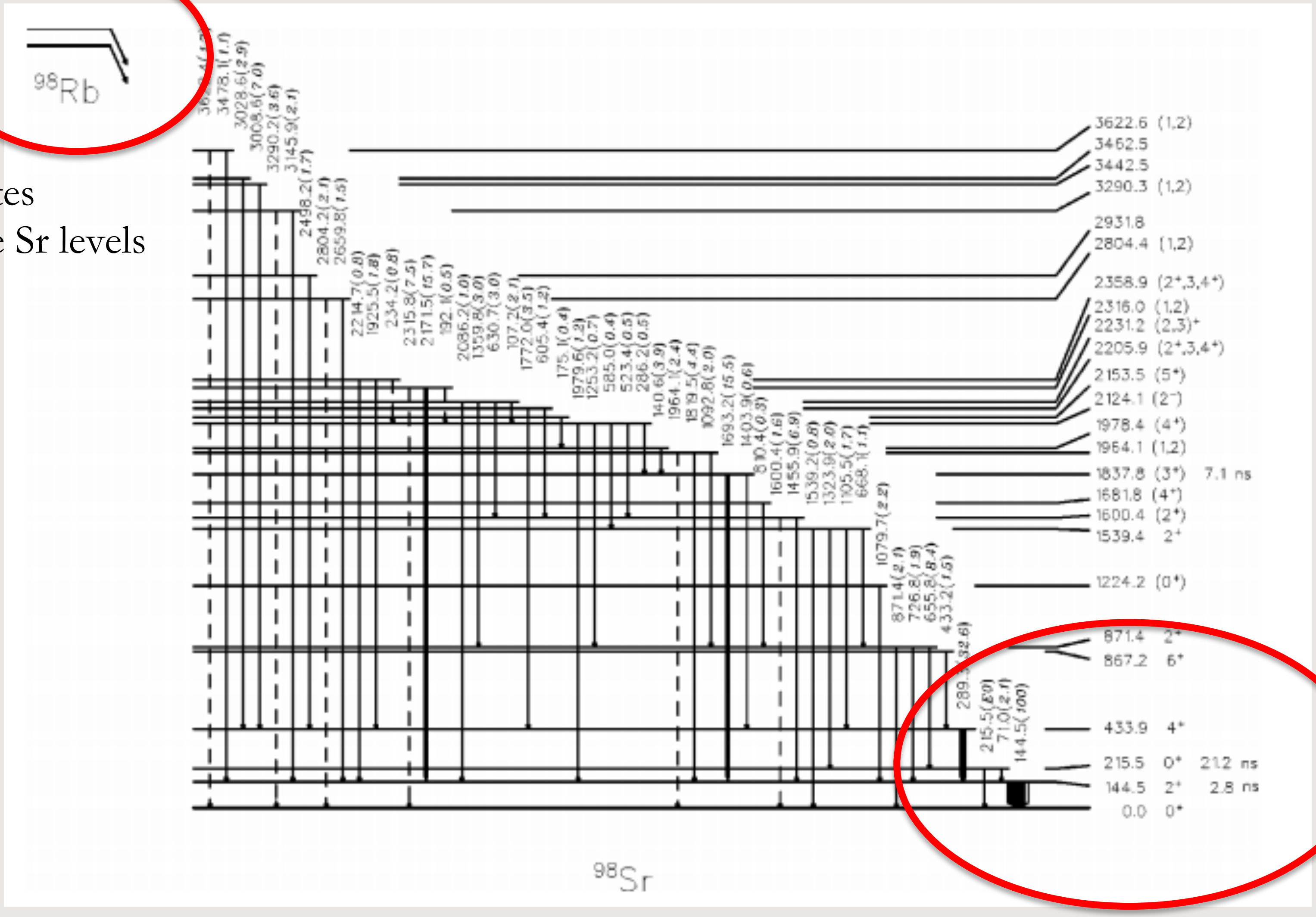
J. Park et al. Phys.Rev. C 93, 014315 (2016)
K. Becker et al. Zeitschrift für Physik A Atoms and Nuclei, 319(2):193–203, (1984)
H. Mach et al. Physics Letters B, 230(12):21 – 26, (1989)

In the r-process



In literature

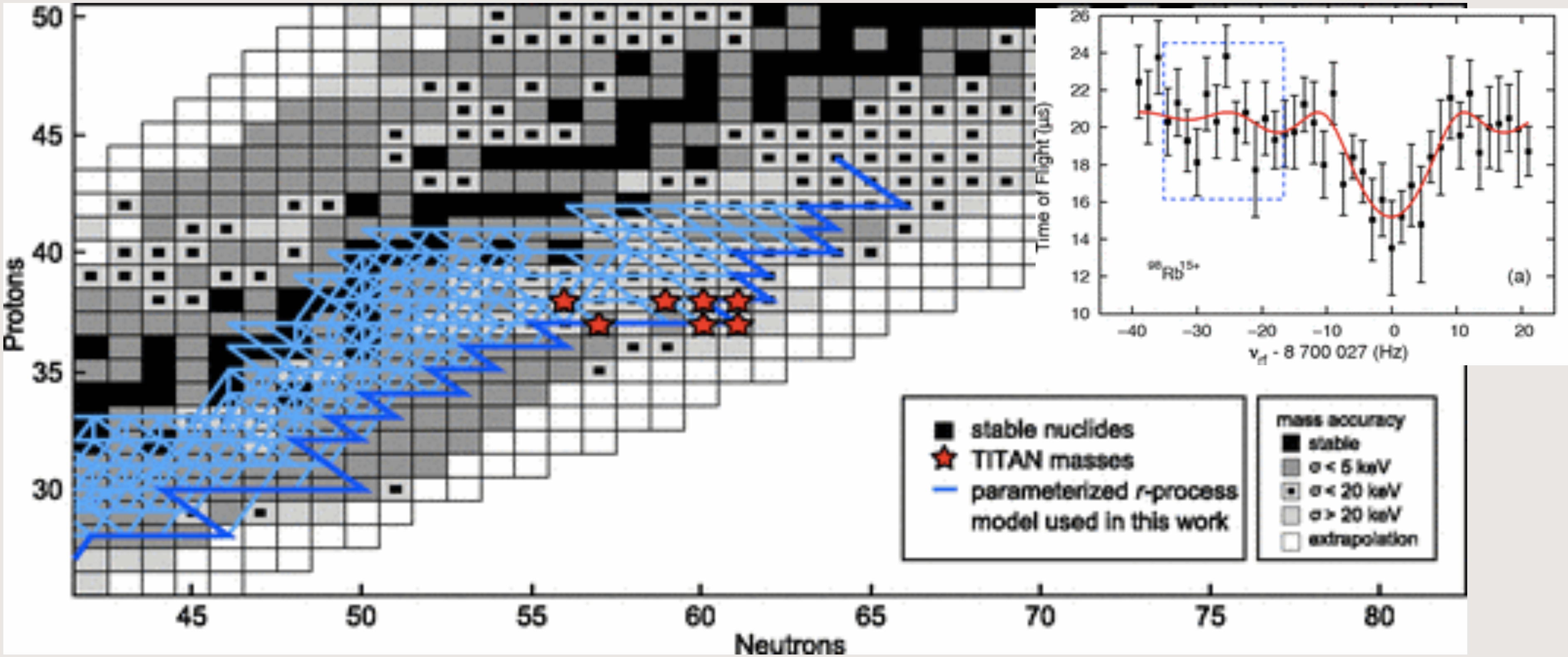
Conventional decay spectroscopy (β–γ)



Two states populate Sr levels

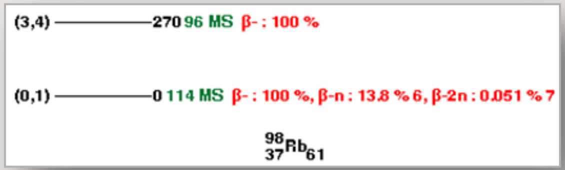
G. Lhersonneau et al. Phys. Rev. C 65 024318 (2002)

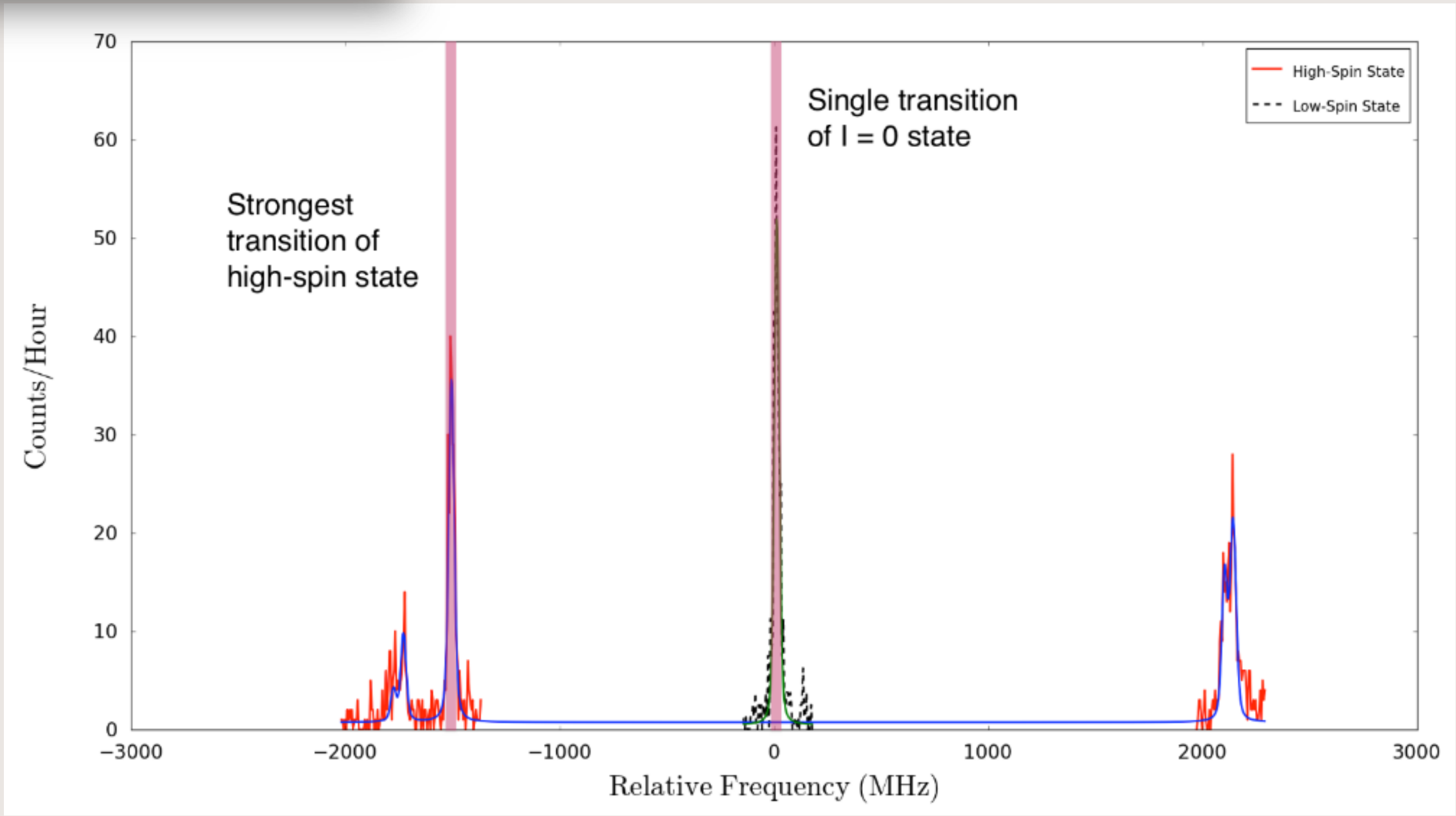
Mass measurement of 98Rb - TITAN



V. V. Simon et. al, Phys. Rev. C **85**, 064308 2012

^{98}Rb – hyperfine structure





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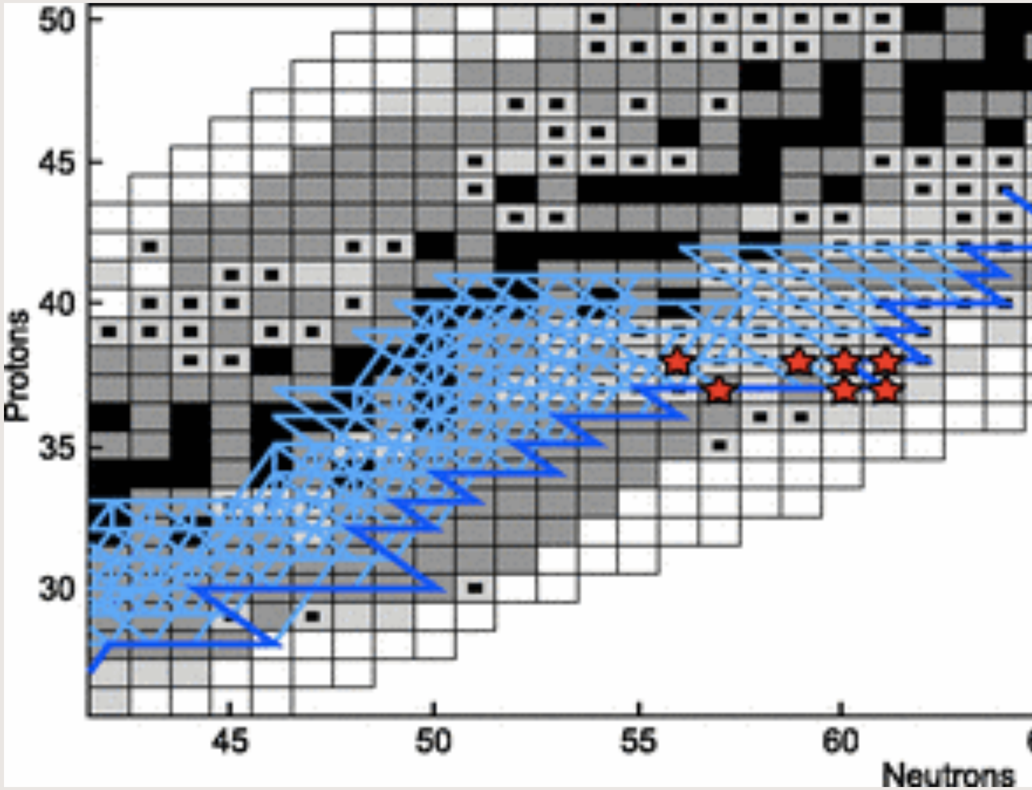

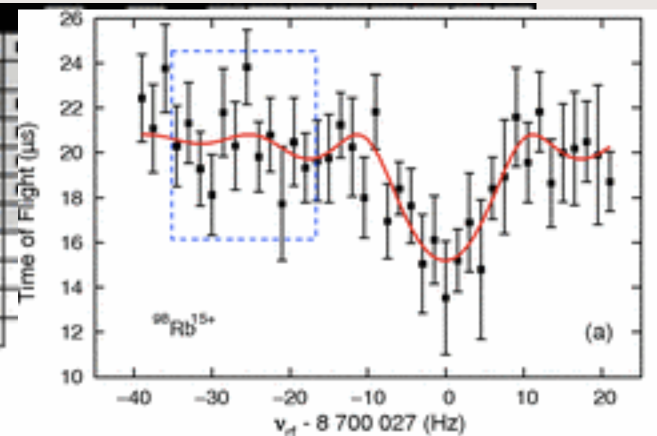

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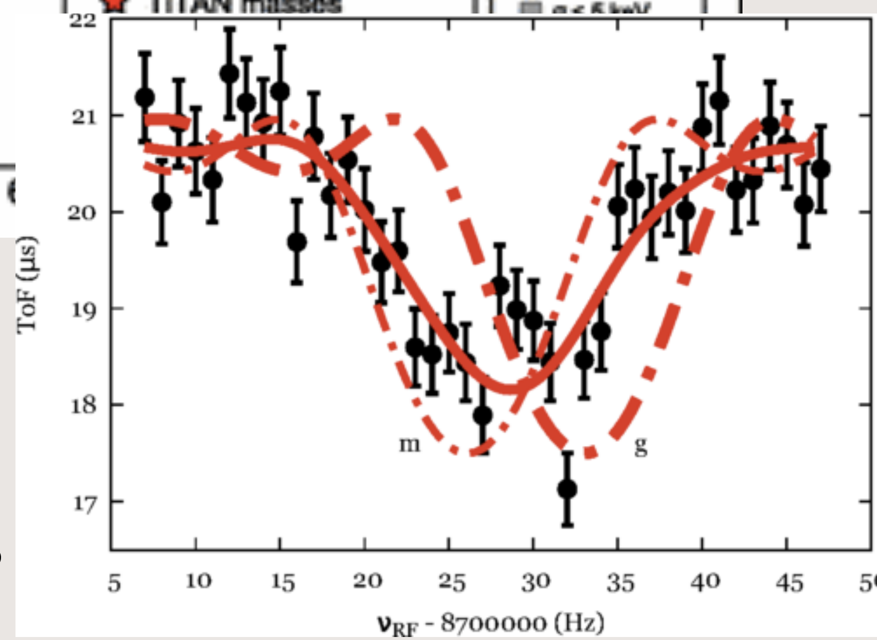
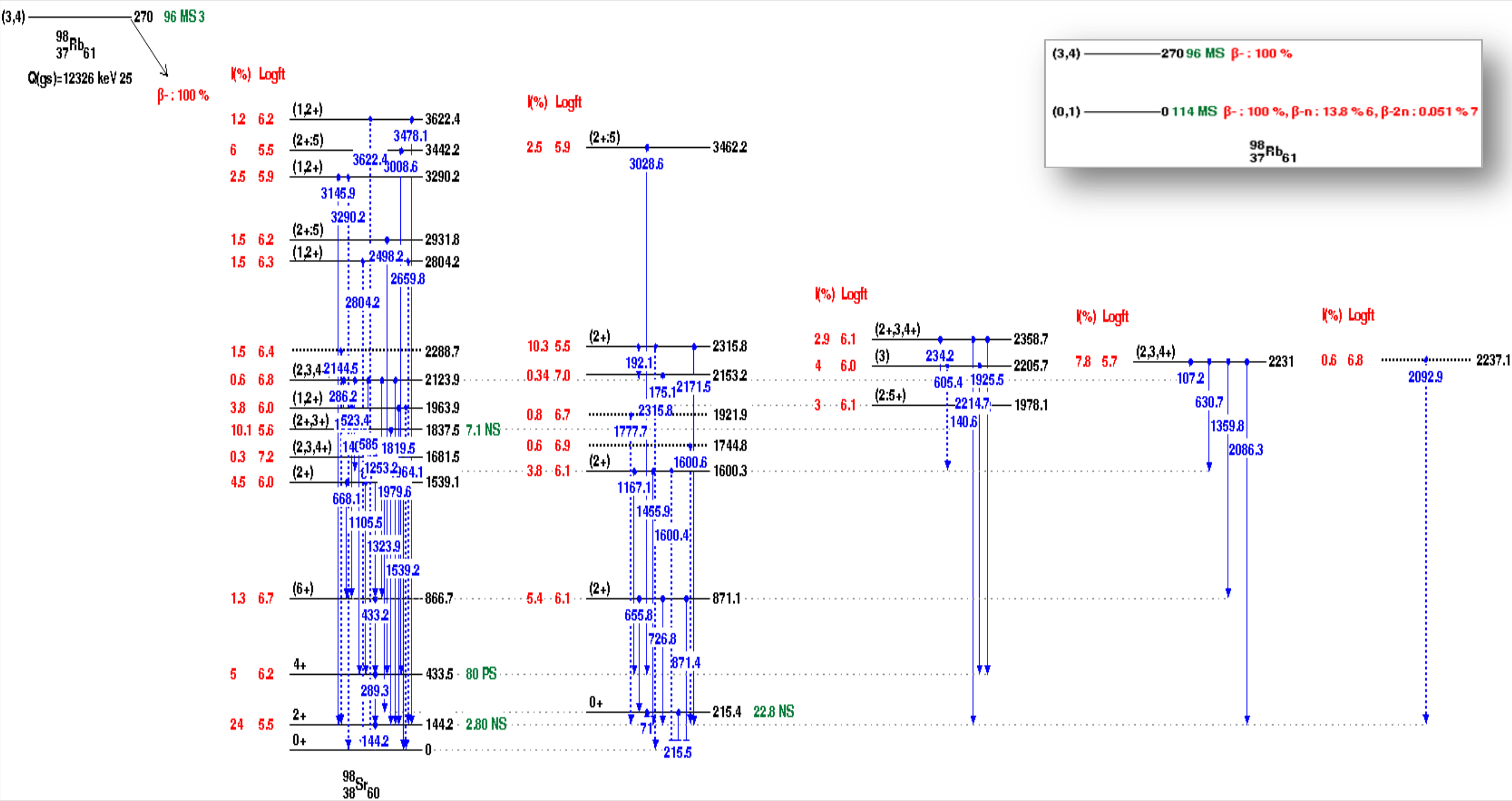


R. Klawitter et. al. Phys. Rev. C **93**, 045807 2016

Conventional decay spectroscopy (β–γ)



Memory refreshers

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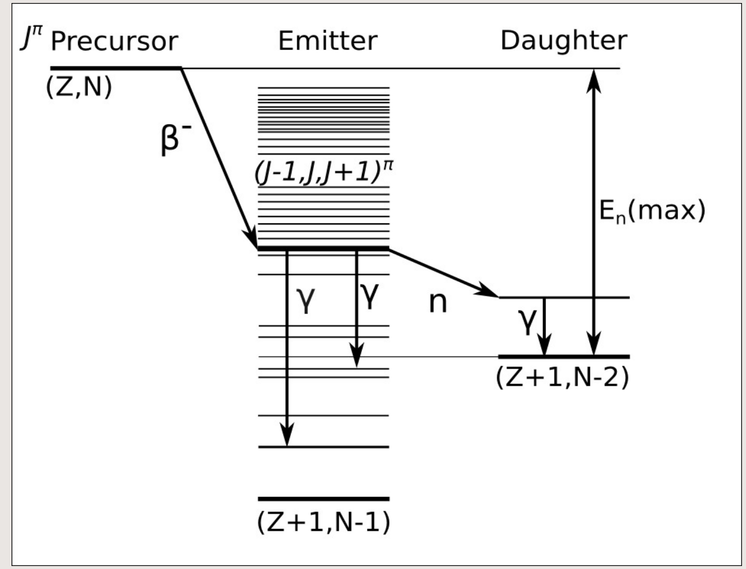
beta decay and gamma de-excitation

- β^- decay (Z+1, N-1)

  $^{14}C \rightarrow {}^{14}N + e + \nu$



Rules for gamma emission

Radiation type	Name	$l = \Delta I$	$\Delta\pi$
E1	Electric dipole	1	Yes
M1	Magnetic dipole	1	No
E2	Electric quadrupole	2	No
M2	Magnetic quadrupole	2	Yes
E3	Electric Octupole	3	Yes
M3	Magnetic Octupole	3	No
E4	Electric hexadecapole	4	No
M4	Magnetic hexadecapole	4	Yes

Rules for beta decay

Decay type	Change in parity	Change in angular momentum
F	no	$\Delta J = 0$
GT	no	$\Delta J = 0, \pm 1$

Decay type	ΔJ	ΔT	$\Delta \pi$	log(ft)
Superallowed	$0^+ \rightarrow 0^+$	0	no	3.1-3.6
Allowed	0,1	0,1	no	2.9-10
First Forbidden	0,1,2	0,1	yes	5-19
Second Forbidden	1,2,3	0,1	no	10-18
Third Forbidden	2,3,4	0,1	yes	17-22
Fourth Forbidden	3,4,5	0,1	no	22-24

Atomic structure

Quantum numbers to describe atomic levels:

Principal quantisation $n = 1, 2, 3,$

Angular momentum $l = 0, . . . , n - 1$

Magnetic substate $m = -l, . . . , 0, . . . , l$

Total angular momentum $j = l \pm ½ ;$ $j > 0.$

Realistic potential:

$$V(r) = V_{Coulomb}^{(r-1)} + \underbrace{V_{Dipole}^{(r-3)} + V_{Quadrupole}^{(r-5)}} + . . .$$

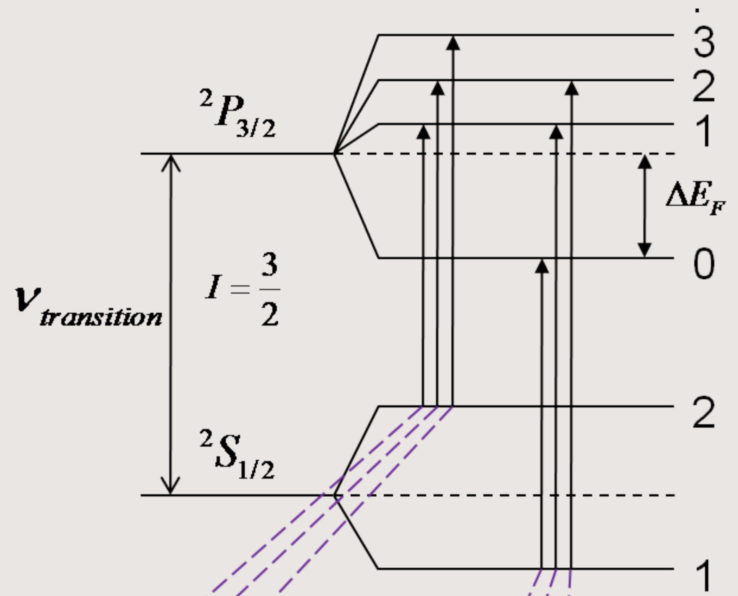
perturbation results in the breaking the degeneracy of electronic states into hyperfine levels

Hyperfine interactions

- Hyperfine interaction couples the electron angular momentum (J) and nuclear spin (I)
- The total angular momentum: $\vec{F} = \vec{I} + \vec{J}$

$$\Delta E_F = \frac{1}{2} AC + B \frac{\frac{3}{4}C(C+1) - I(I+1)J(J+1)}{2I(I+1)J(J+1)}$$

$$C = F(F+1) - I(I+1) - J(J+1)$$

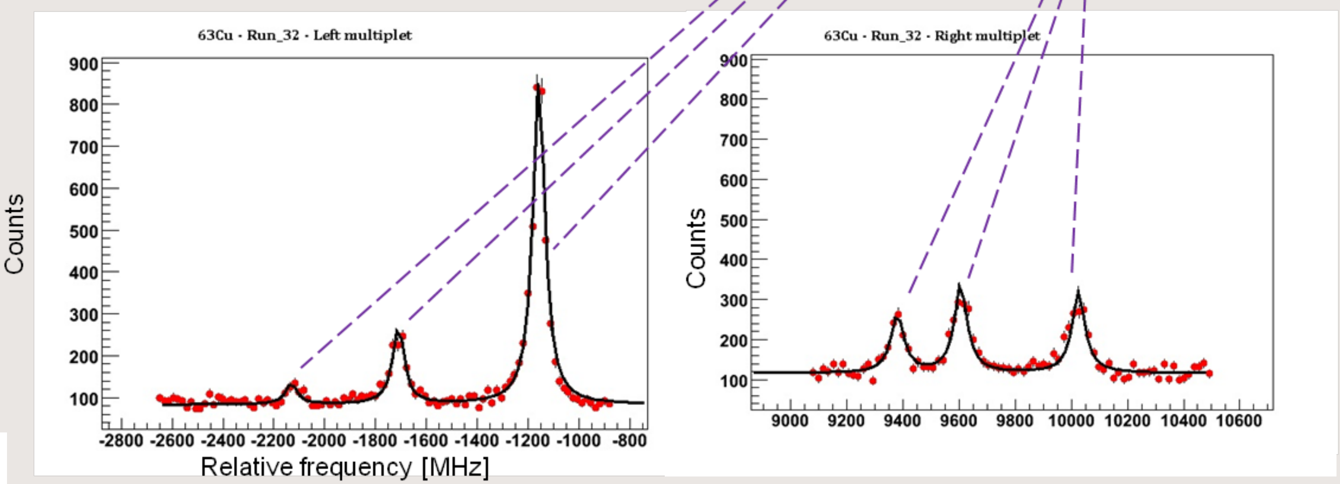


- Magnetic dipole HF parameter:

$$A = \frac{\mu_I B_J}{IJ}$$

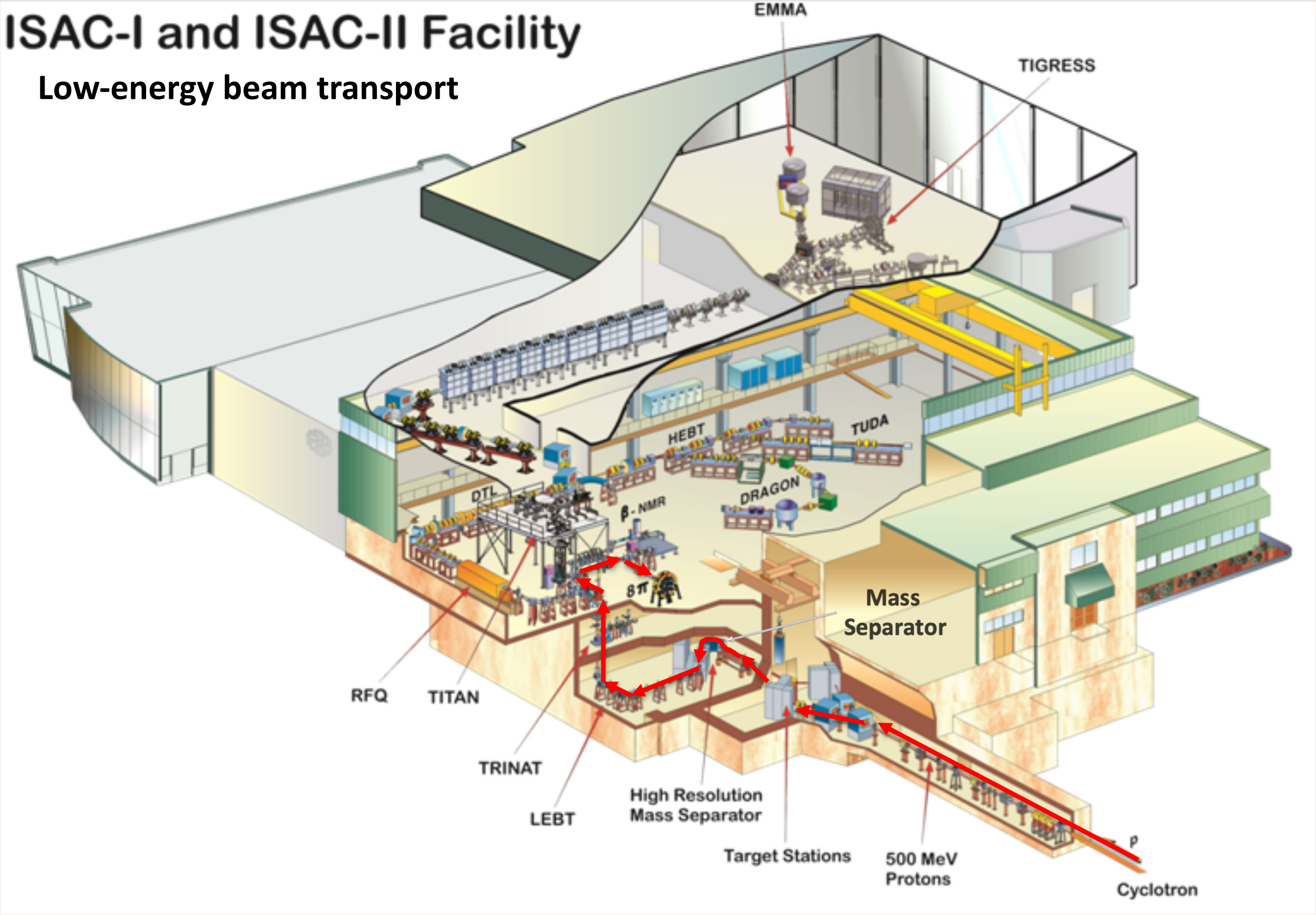
- Electric quadrupole HF parameter:

$$B = eQV_{zz}$$

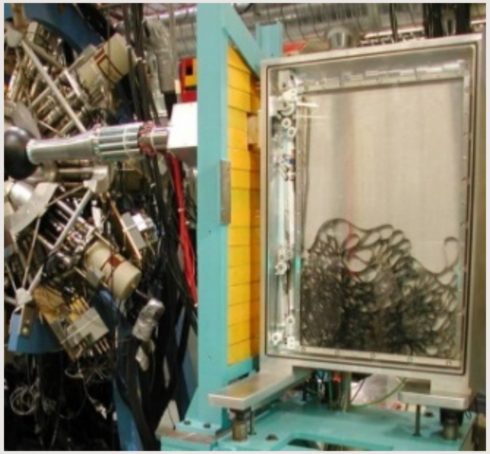


$$\Delta l = \pm 1$$
$$\Delta J = 0, \pm 1, \quad J = 0 \nrightarrow 0$$
$$\Delta F = 0, \pm 1, \quad F = 0 \nrightarrow 0$$

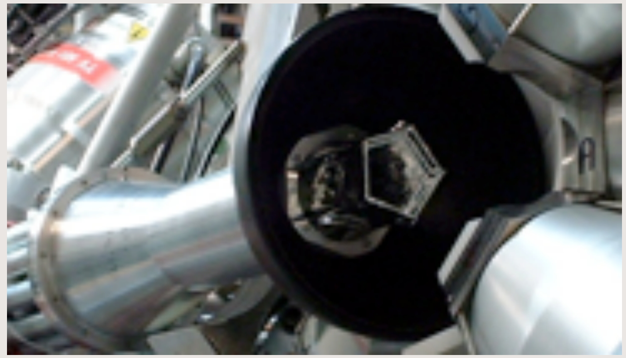
The experimental equipment



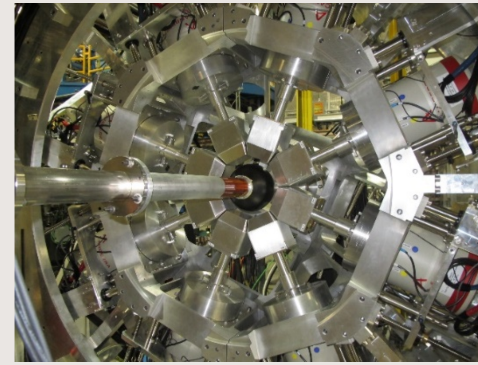
Experimental setup: Suite of auxiliary detectors



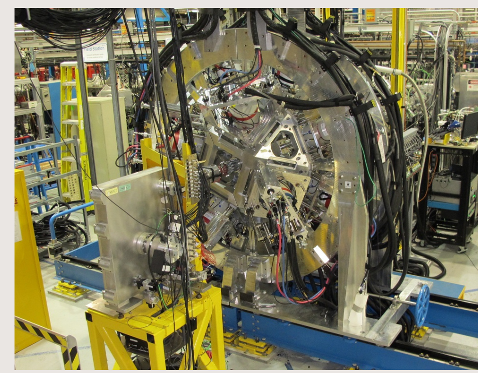
Fast, in-vacuum tape system *removes long lived activity*

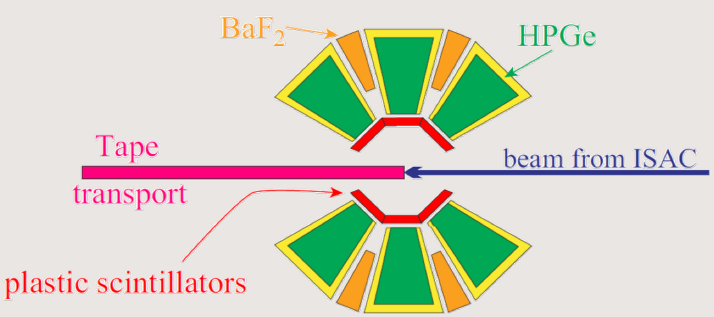


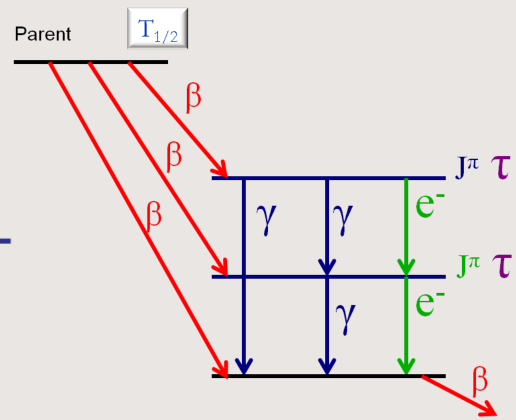
10+10 plastic scintillators
Detects beta decays and determines branching ratios 2



16 HPGe detectors







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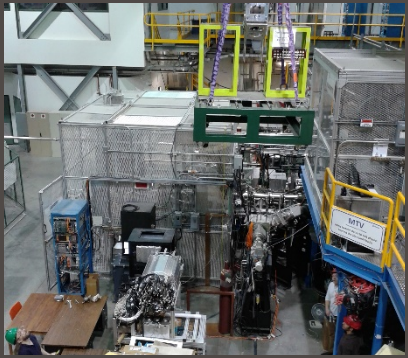
Resonant Ionization with a high resolution at the first step of selectivity

For decay-spectroscopy

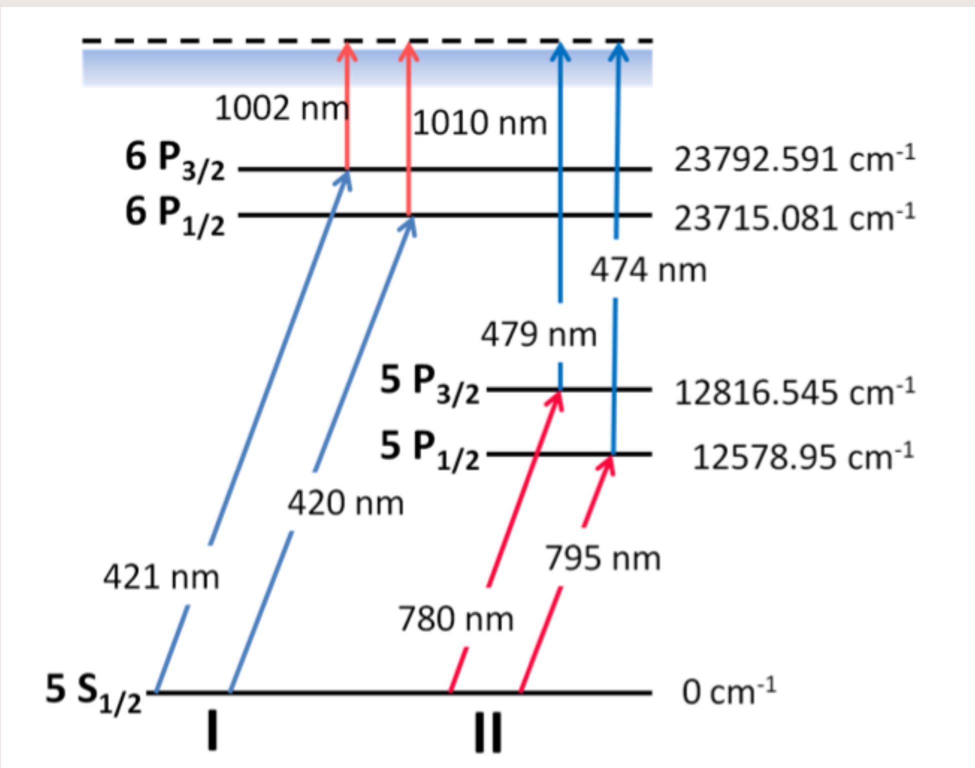


Description of Experiment

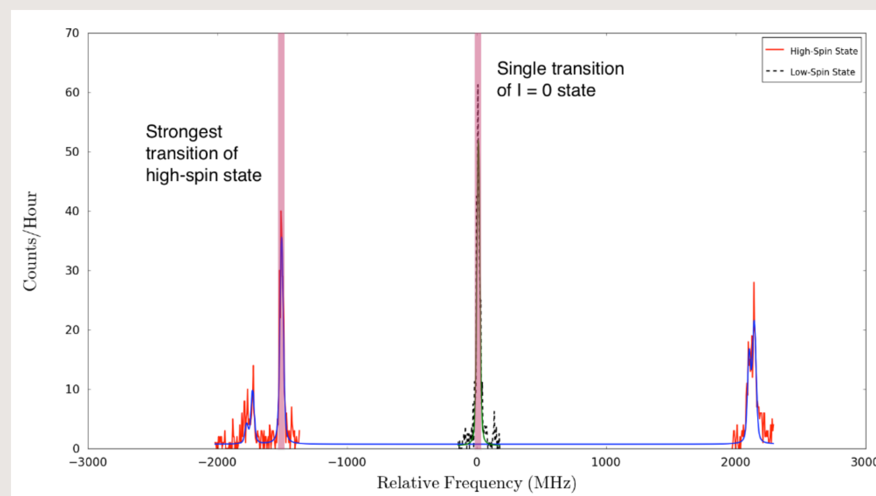
Ionization schemes:

I Frequency doubled light from Ti:Sa to access 420 nm. Frequency doubled light from Nd:YAG at 532 nm.

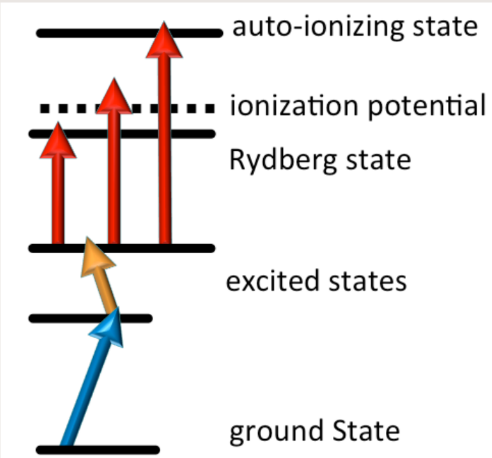
II Fundamental light from Ti:Sa at 780 nm. Frequency tripled light from Nd:YAG at 355 nm.



Selectively ionize states using hyperfine structure already measured on D2 transition (780 nm) by laser spectroscopy group.

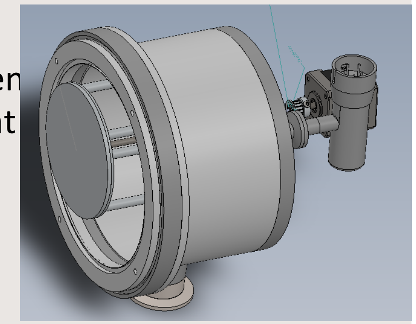


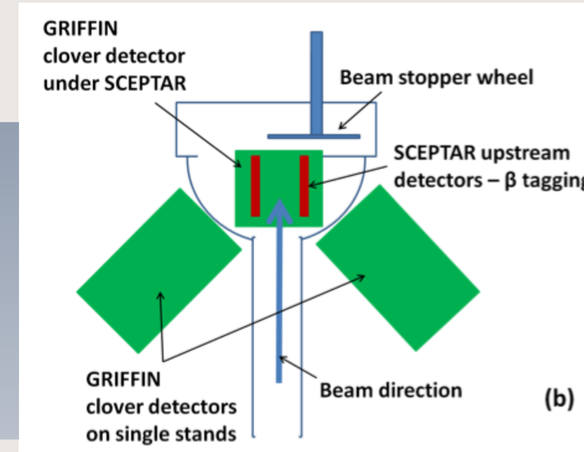
Description of Experiment

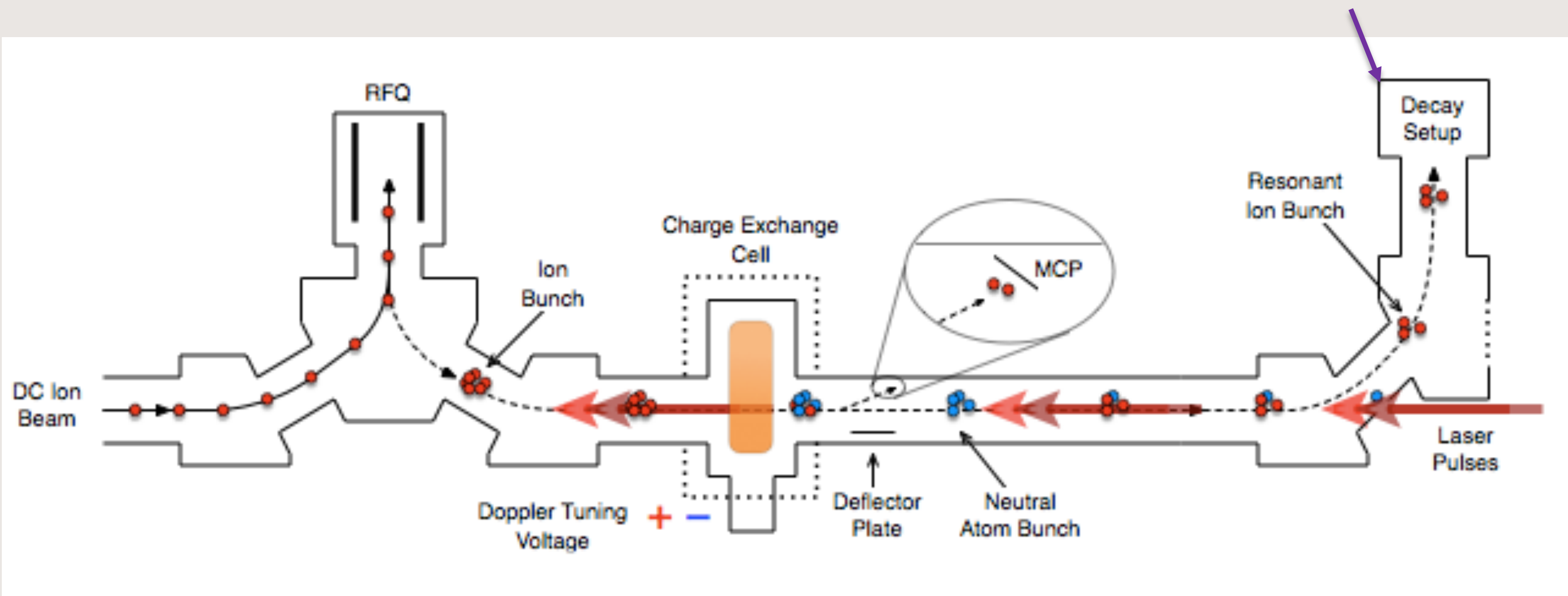


Resonant ionization in CFBS beam-line:

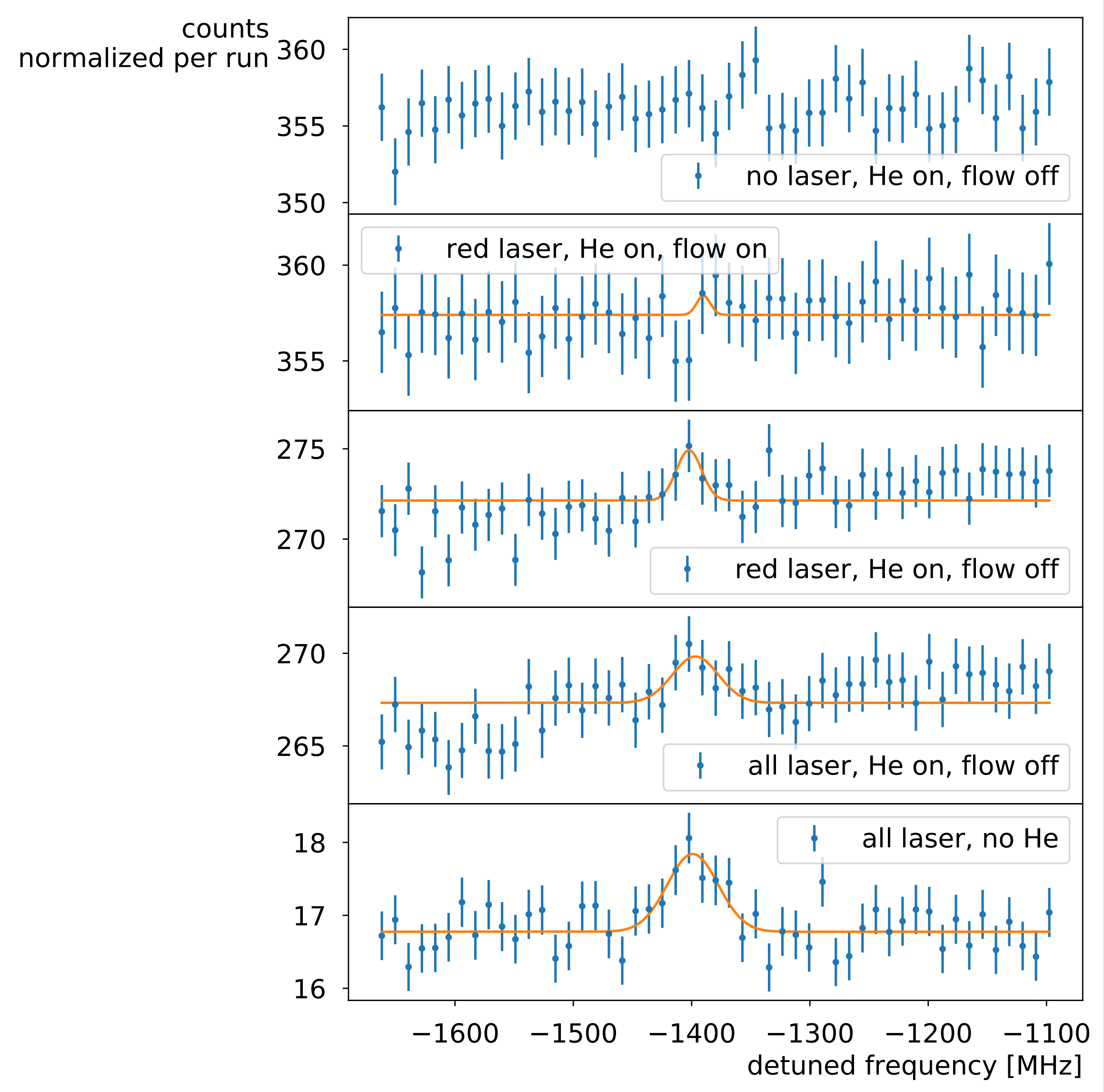
Isomeric/ ground state selectively ionized and then delivered to decay setup at end of OSAKA line.







Proved separation of stable ^{85,87}Rb



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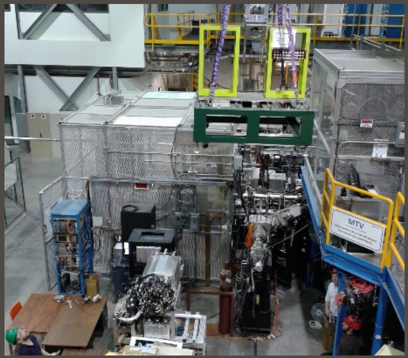
Pros and cons

- What do we gain?
  - Beam purification
  - Detailed feeding from ground and isomeric states

    OR
  - Detailed feeding from a particular isotope
  - Hyperfine structure
    - Spin of ground state (and possible excited isomeric states)
    - Magnetic moments and maybe static quadrupole moment

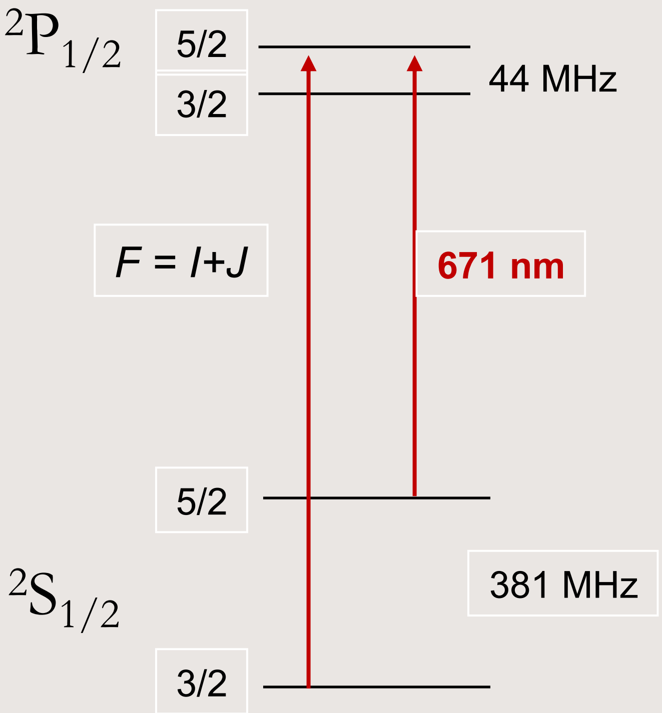
- What's the catch?
  - Case by case experiment with different atomic structure
  - Laser for transitions needed
    - May need multiple steps to ionization
    - Cater for the different types and powers of the lasers (can lead to loss in resolution of the first selection step)
  - Beam to ion efficiency can vary from 1% to 10% so hard to do with very low intensity exotic beams
  - Need very good vacuum (10^{-8} torr) to reduce collisional ionization

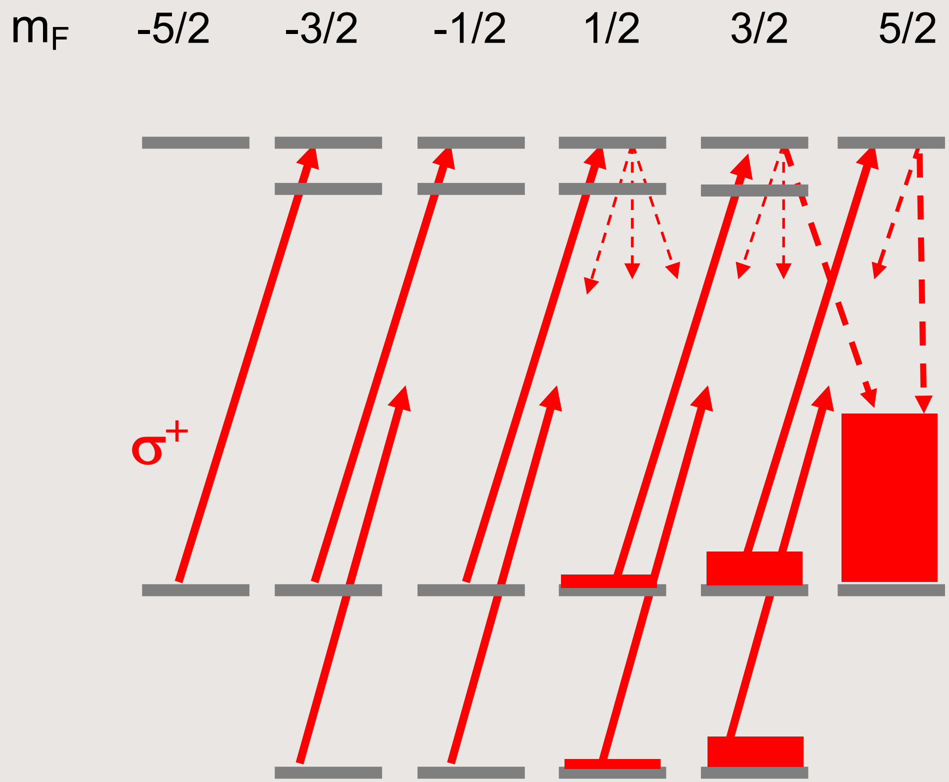
Use of polarized beams for decay spectroscopy



Polarization from optical pumping of ^{8}Li atoms

Hyperfine structure

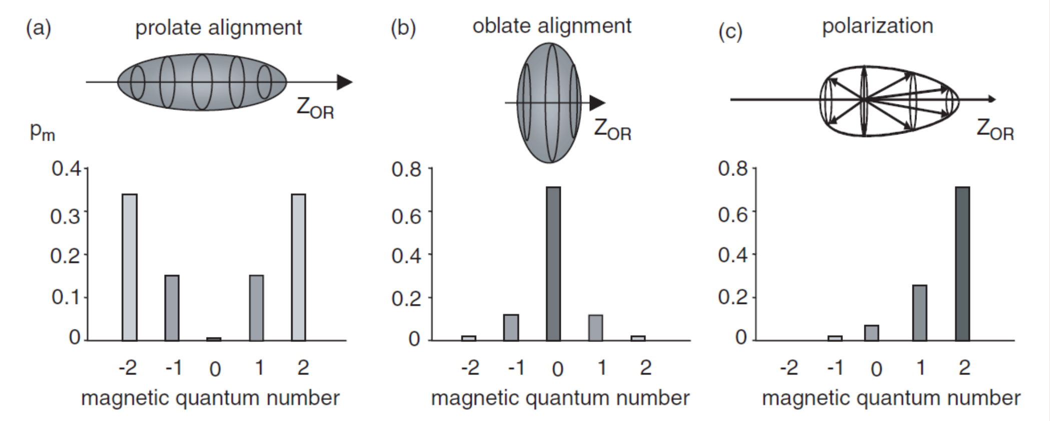


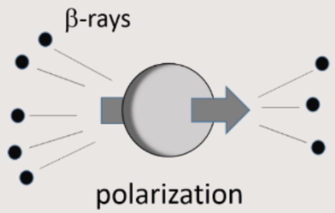


…showing magnetic substates

- Electro-optic modulator (EOM) puts 381 MHz sidebands on laser frequency, and so both ground state hyperfine levels are pumped.

Decay spectroscopy (β–γ) of polarized nuclei





The asymmetry parameter A is a constant depending on the daughter state spin value.

Spin polarization is measured by counting the beta decay along the orientation axis

angular distribution of β from polarized nucleus

allowed transition

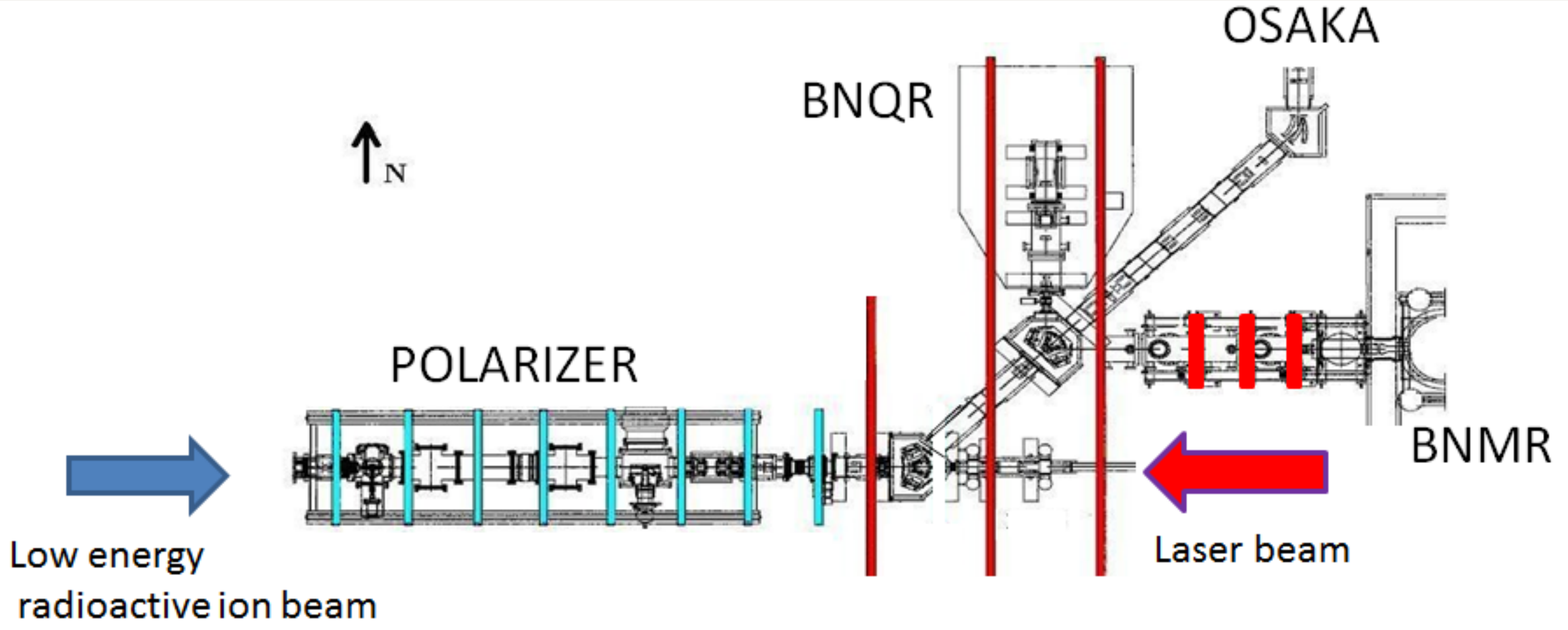
$$W(\theta) \cong 1 + AP\cos\theta$$

A : asymmetry parameter of β-decay
P : spin polarization of parent nucleus
θ : emission angle of β with respect to polarization axis

$$A \begin{cases} = -1 & (I_f = I_i - 1), \\ \backsimeq \dfrac{-1}{I_i + 1} & (I_f = I_i), \\ = \dfrac{I_i}{I_i + 1} & (I_f = I_i + 1). \end{cases}$$

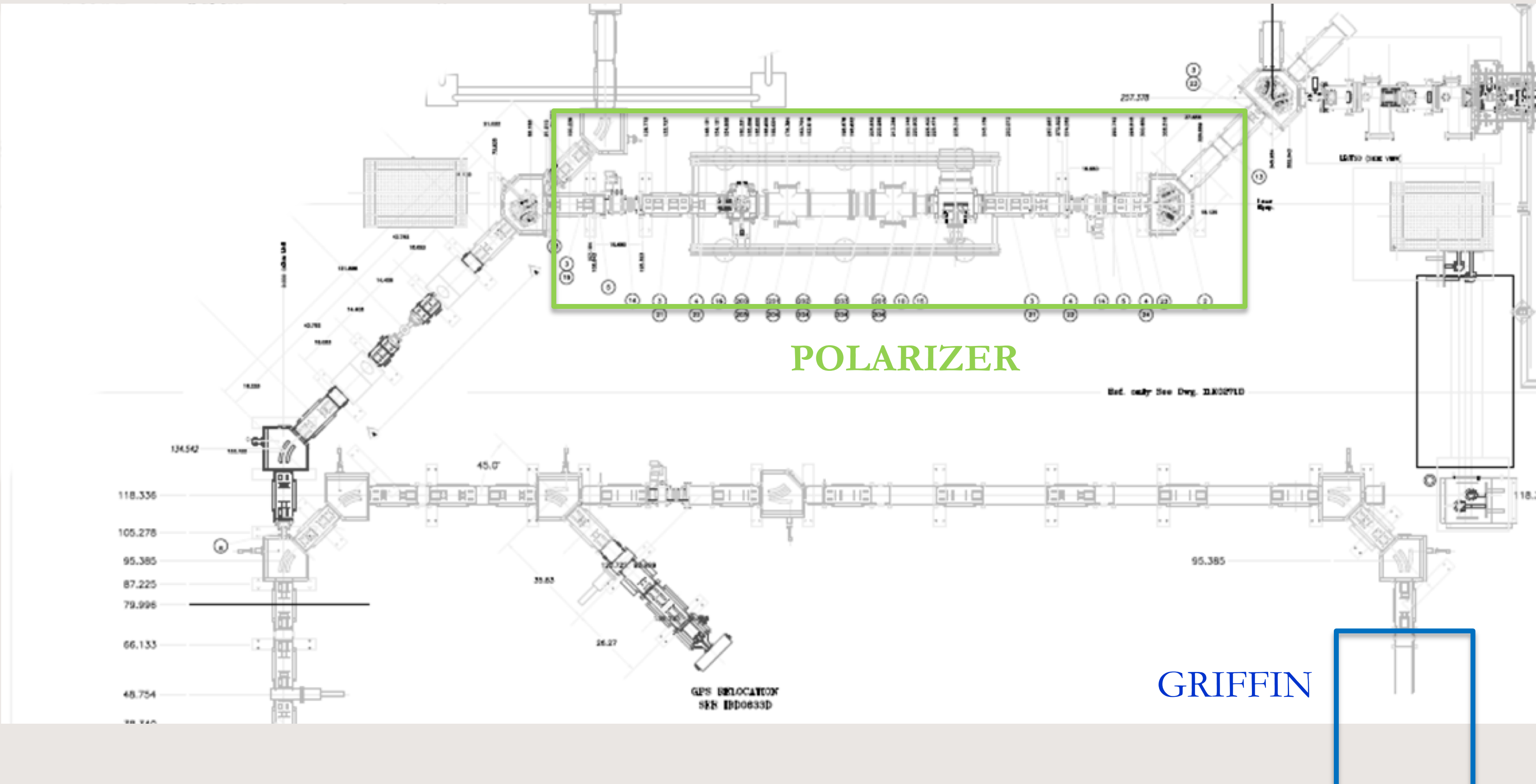
T. Shimoda, et al. Hyperfine Interact., 225 (2014), p 183

Beamline layout in ISAC-I



- Collinear polarized light interacts with atom/ion beam to produce nuclear-spin polarized beams (longitudinal or transverse)
- Magnetic coils (light blue) provide ~10 gauss field along Polarizer axis
- Coils (red) downstream of Polarizer preserve polarization in case of paramagnetic ions whose electronic and magnetic moment strongly couples nuclear spin to outside world.

Join the polarizer beam line to GRIFFIN



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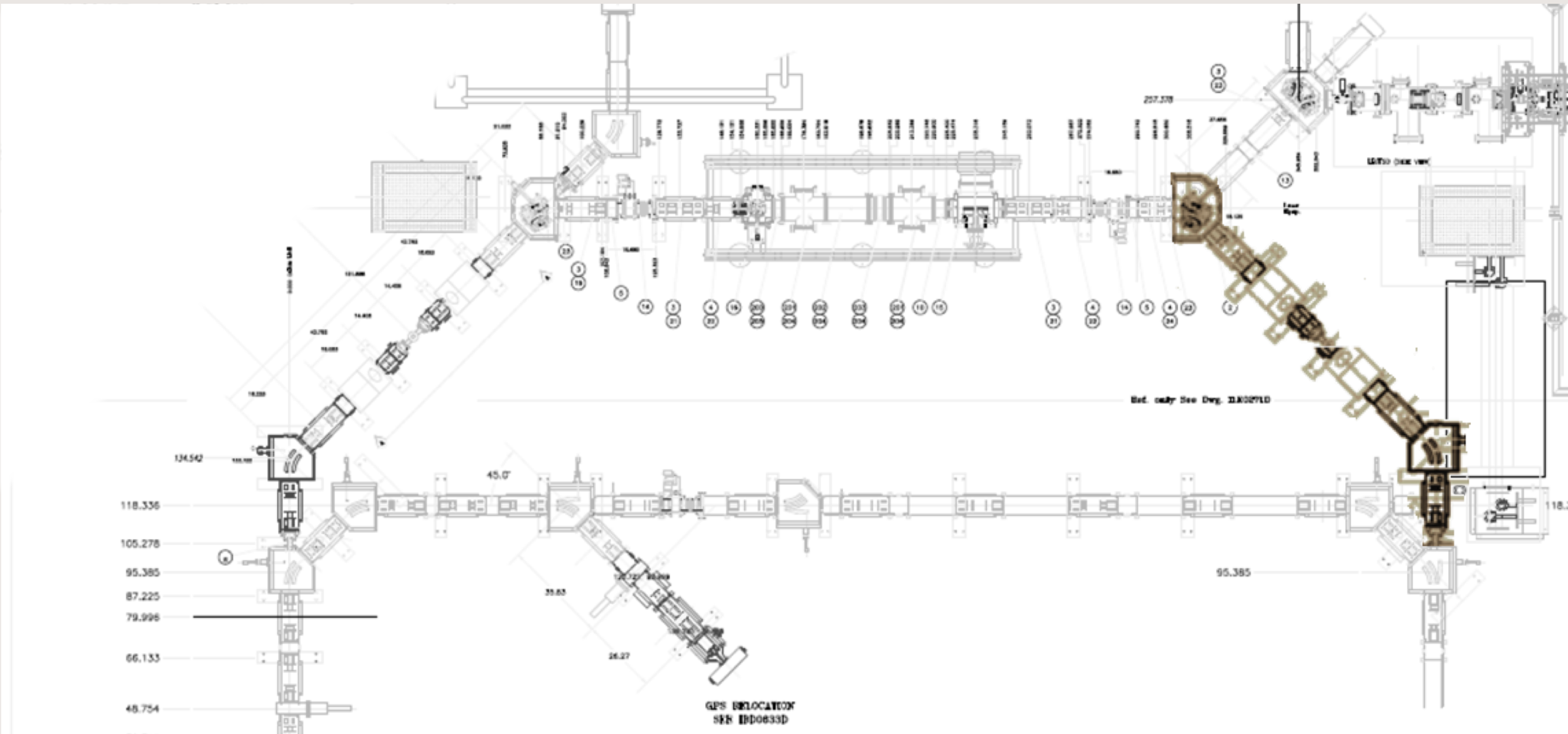
Future of the detailed decay spectroscopy

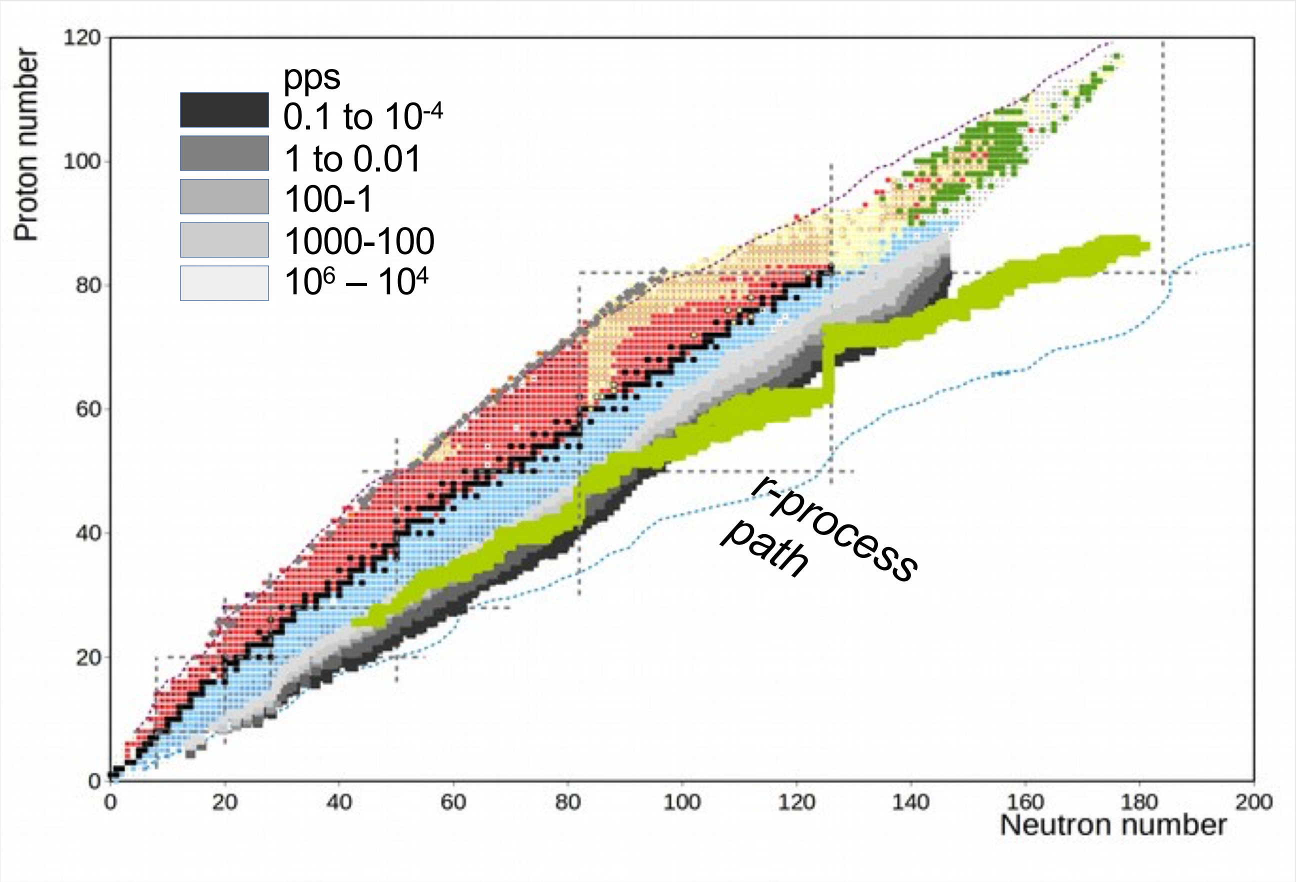


Needs for decay-spectroscopy

- Neutron detectors – for the newly accessible neutron rich nuclei at FRIB, ARIEL (RIKEN)
  - NeXT detector – TOF energy
  - ORNL neutron counter – branching ratios
- High efficiency arrays
  - GRIFFIN – TRIUMF – ISAC I
  - FRIB decay station
- Total decay heat
  - MTAS –ORNL
  - SUN - MSU

Decay Station will measure new data (lifetimes, branching ratios) for most exotic isotopes

- Essential for astrophysical r-process simulations
- Critical to develop nuclear structure models relevant for astrophysics



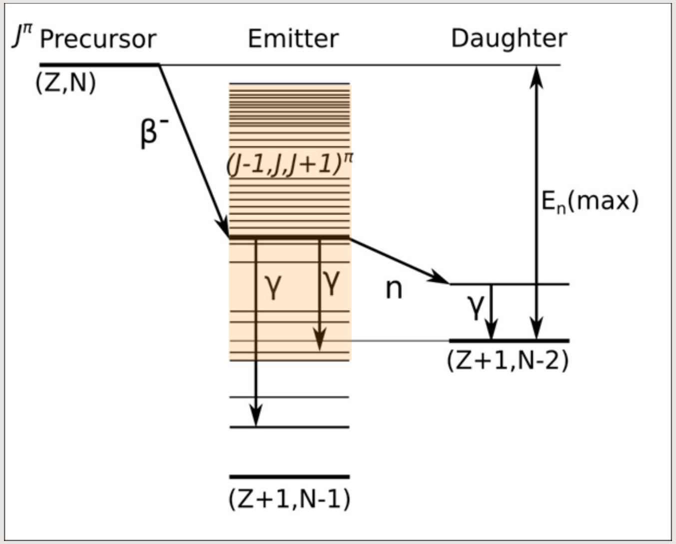
Beta-delayed neutron emission

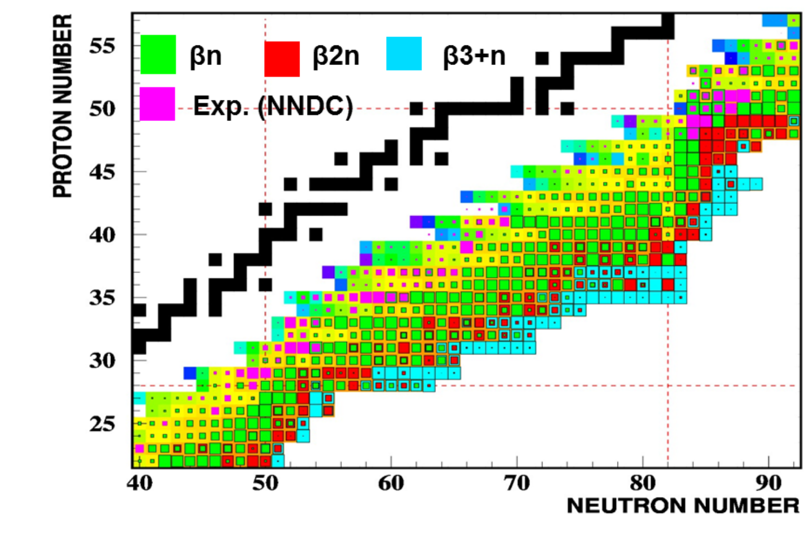
Composite decay mode of neutron-rich nuclei

Far from stability decay energy Q_β increases and neutron separation energy S_n decreases.

- Delayed neutron emission becomes dominant decay mode
- Neutron energy carries the information about excited states in the emitter.

Experimental challenge: reconstruct complete decay pattern with best possible resolution.





Neutron spectroscopy – relatively unexplored field

Neutron array will be an essential part of FRIB Decay Station

Role of structure/statistical model,

1n emission from 2n unbound states ?

Decay of r-process nucleus ^{124}Nb: from N=82 to Z=50

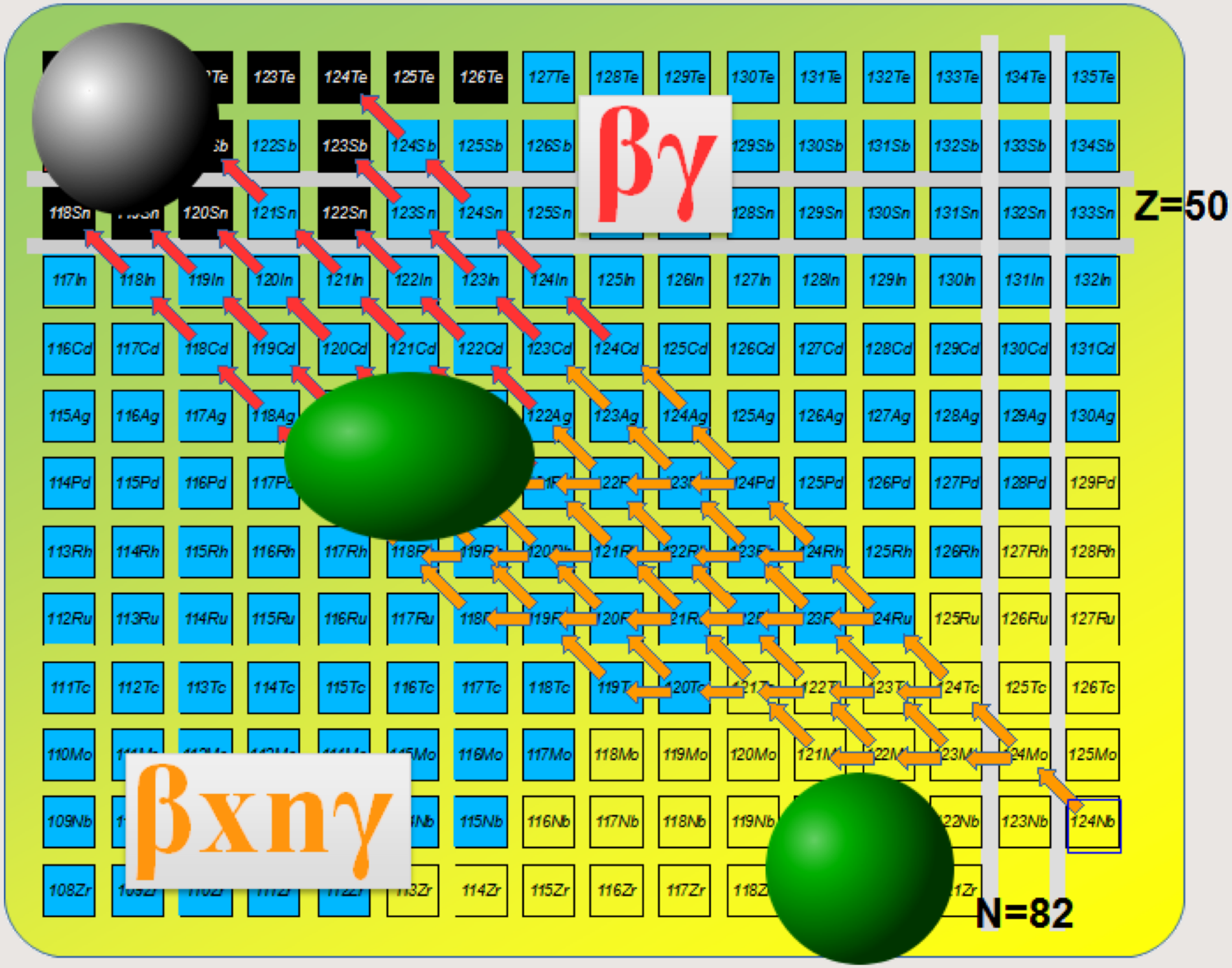
Q_β ~ 21 MeV
$T_{1/2}$ ~2 ms
Decay modes:
βγ, βn, β2n, β3n…

Decay of ^{124}Nb:

~30 isotopes in 1s

Releases ~100 MeV

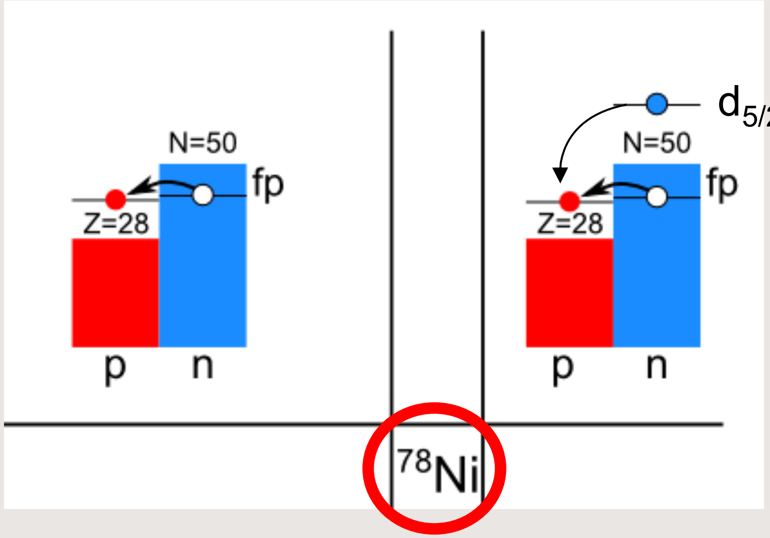
$T_{1/2}$<1s

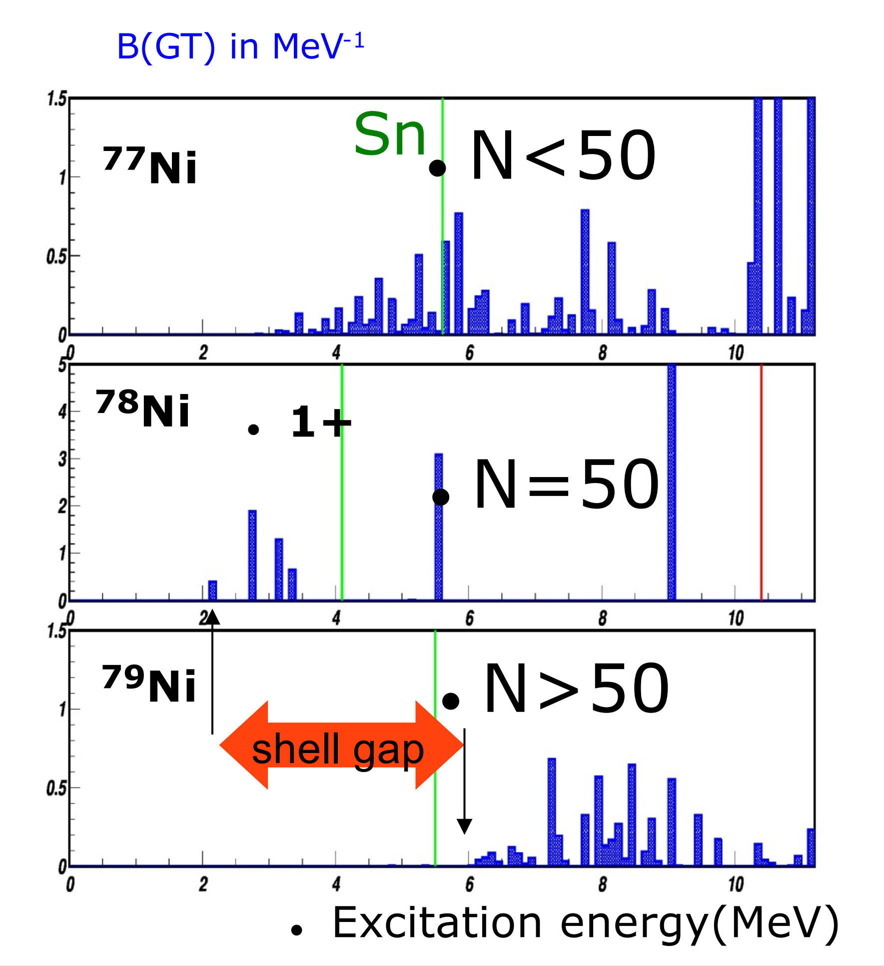


Effects of the shell gap on the decay of isotopes with N>50

Gamow-Teller operator connects spin-orbit partner orbitals.

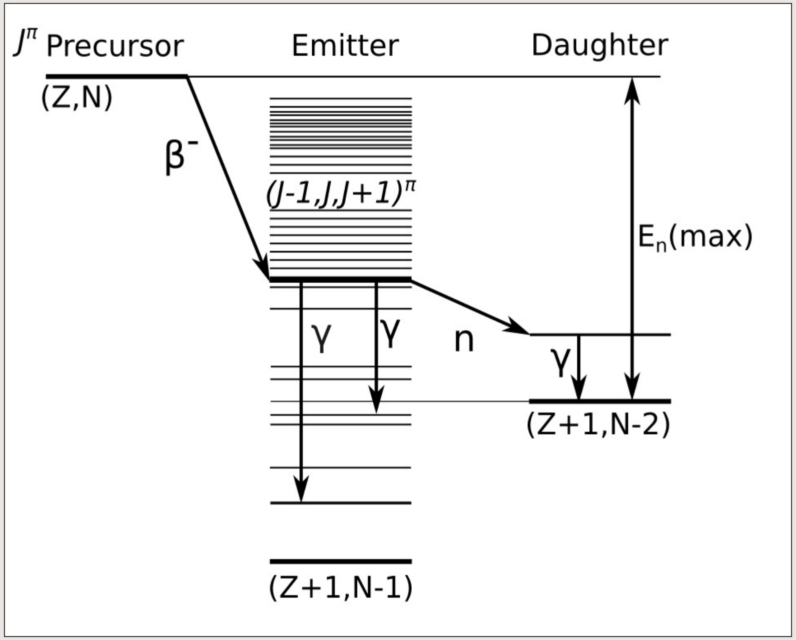
- This mechanism drives beta delayed neutron emission across the N=50 shell-gap.





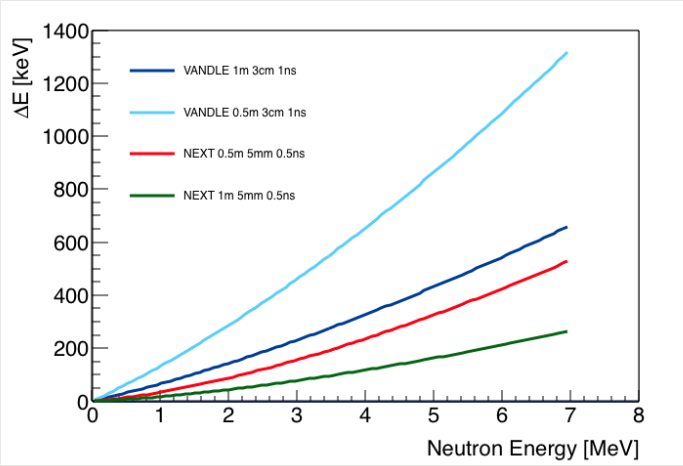
Single particle energies,
effective interactions determine
location and fragmentation of GT strength.

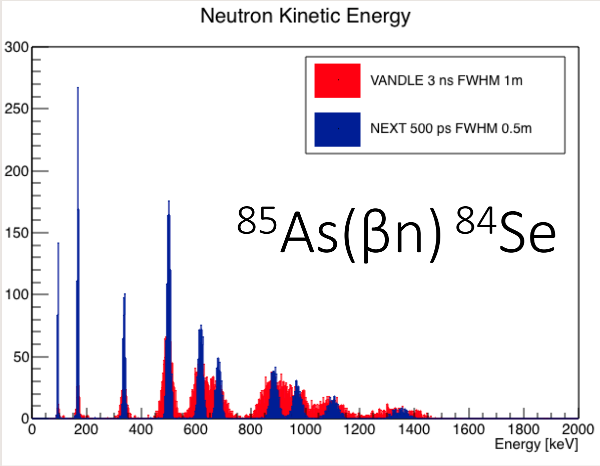
NeXT detector – TOF detection for unbound states

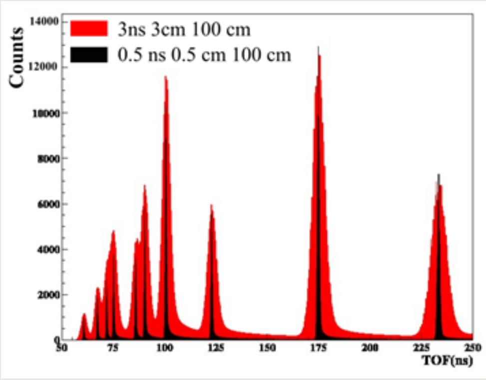


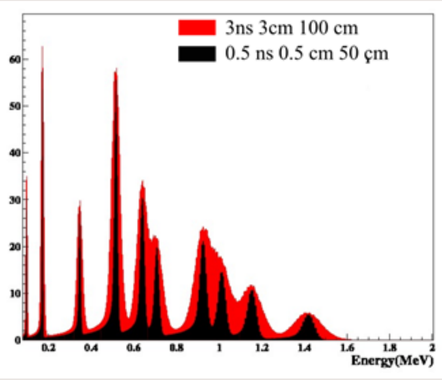
Improved Energy Resolution

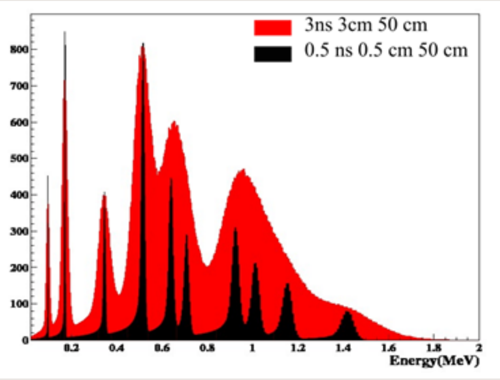
- Better Localization and ToF resolution → Energy Resolution increases without loss of efficiency.











Neutron dEtector with Tracking

NEXT concept: tiled thin scintillator with the side light readout.

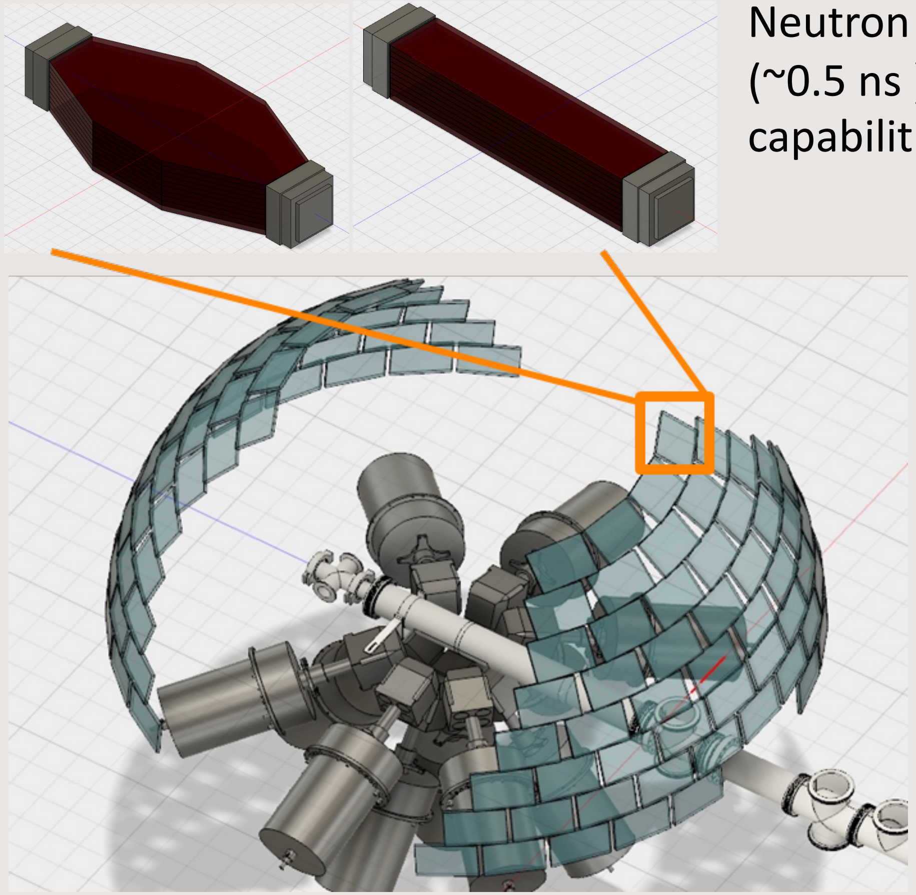
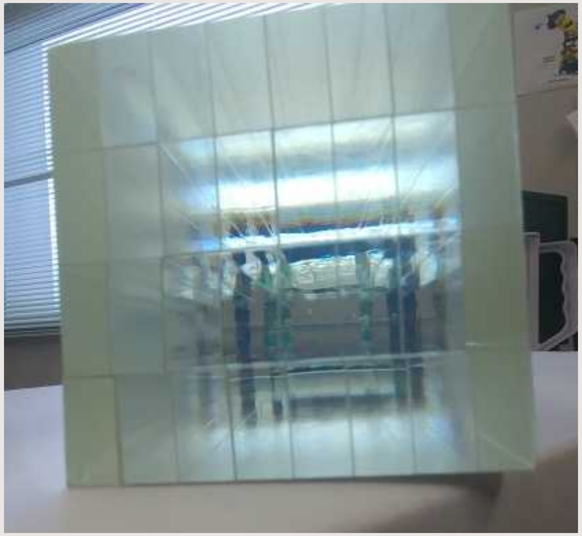


Image credit: S. Munoz and T. King

Neutron time-of-flight detector with good timing (~0.5 ns) and neutron/gamma discrimination capabilities for decay and reactions studies

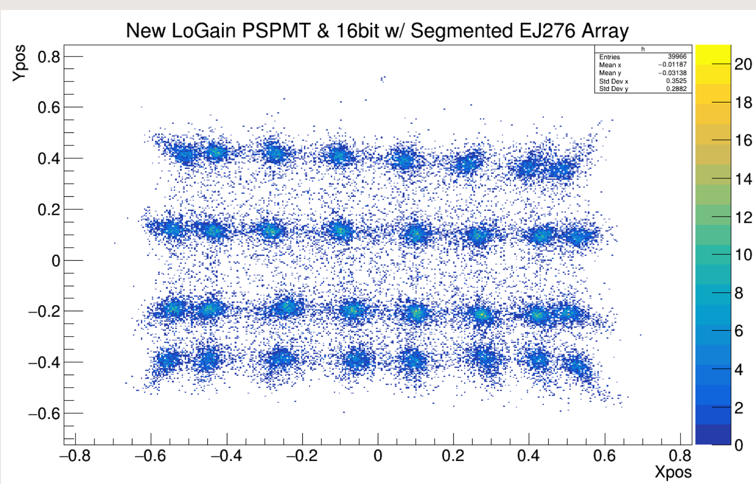
- Silicon Photomultiplier (SiPM) or flat panel PMT (H12) readout → Δt≈600 ps or better
- Neutron/Gamma discrimination plastic
- Improvement in energy resolution by interaction localization
- Sensitivity from 100 keV to 10 MeV neutrons
- Flexible geometry for decay and reactions studies
- Multi-layered modules with ΔL=5 mm
- Efficiencies: ~50% intrinsic / ~25% geometric

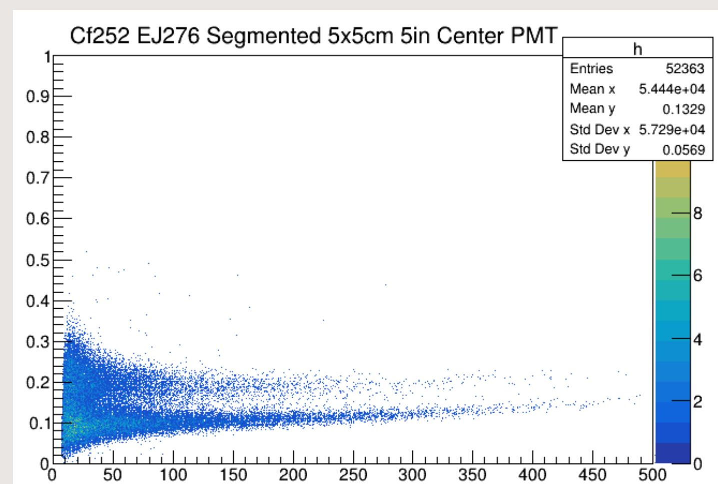
NEXT prototype



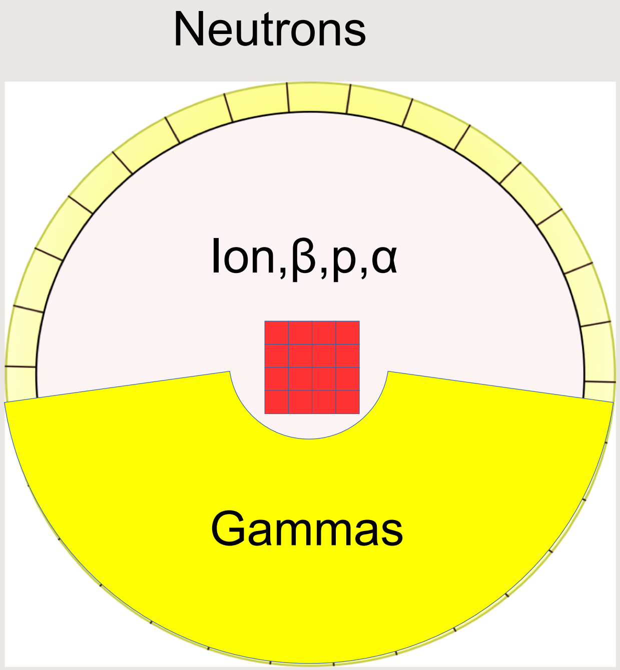
Hamamatsu Multi-anode PMT with Anger Logic Readout

Custom Modular SiPM arrays being designed at UTK.



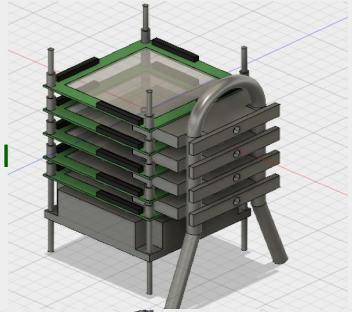


Decay station at FRIB – beta detection

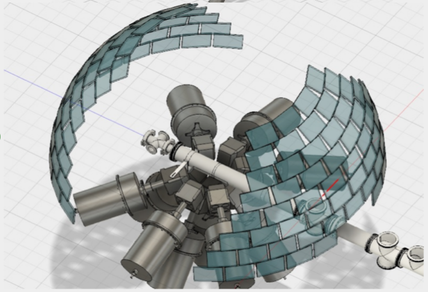


Early funding needed:

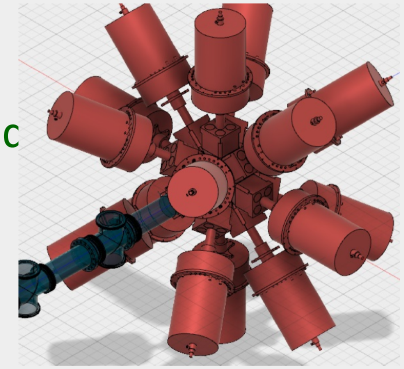
Silicon strip detector arı



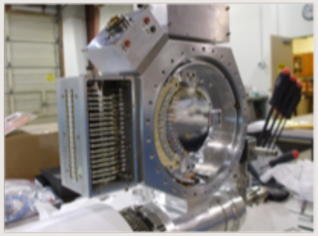
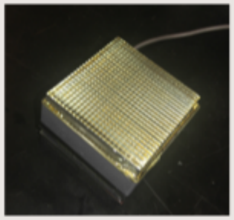
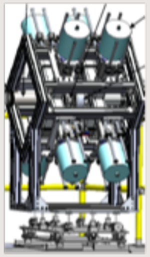
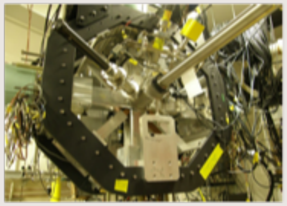
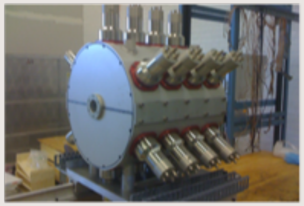
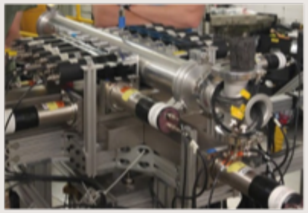
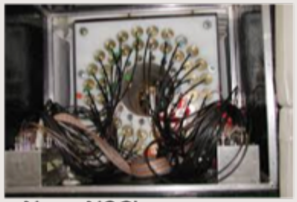
New array for neutro



Array of large clover c



Decay spectroscopy groups and existing equipment

 BCS NSCL	 GeDSSD NSCL	 PSPMT UTK
 Clovershare NSCL	 CARDS ORNL	 X-array ANL
 SUN NSCL	 MTAS ORNL	 HAGRID UTK/Rutgers
 3Hen ORNL	 Nero NSCL	 VANDLE UTK

- An ensemble of equipment currently exists amongst several US research groups and are currently used.

Collaborators

Thank you!

Questions?

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