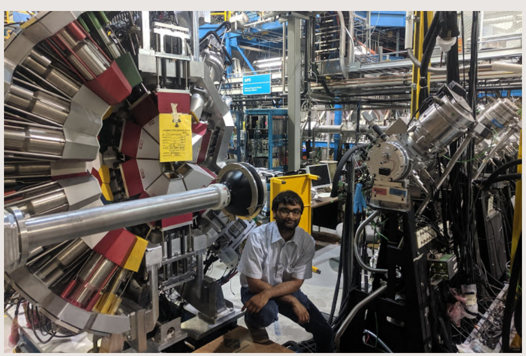
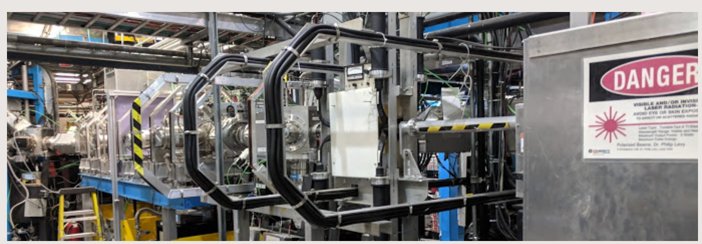
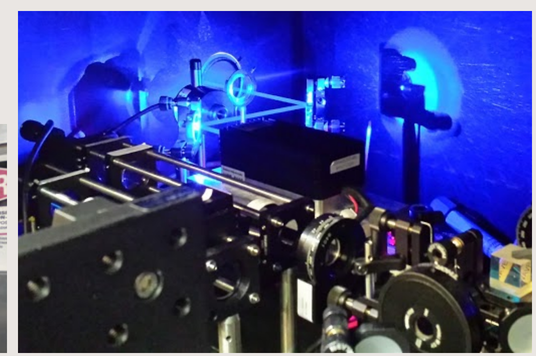
Laser assisted decay spectroscopy
A test case with ^{98}Rb at TRIUMF

Mustafa M. Rajabali
Tennessee Technological University

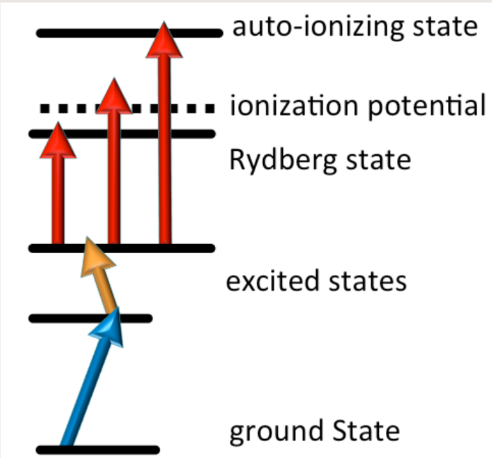





Outline

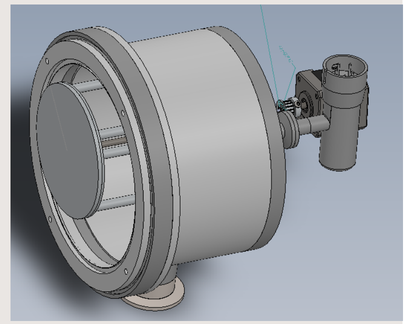
- Decay spectroscopy
  - ^{98}Rb and ^{98}Sr - nuclear structure
  - Overview of the experiment
  - Decay spectroscopy development
- Laser spectroscopy
  - Hyperfine structure
  - Developments for this experiment
- POLARIS
  - Using resonant ionization with high resolution selectivity in the first step
  - With polarized beams – for extracting spins (and parity) with low intensity beams
  - Laser assisted decay spectroscopy – detailed decay spectroscopy at GRIFFIN

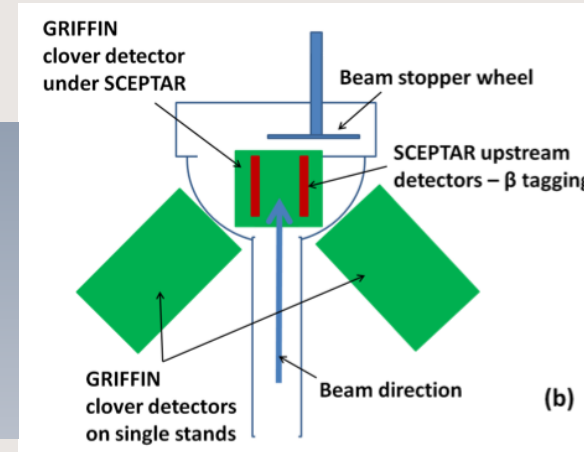
Overview

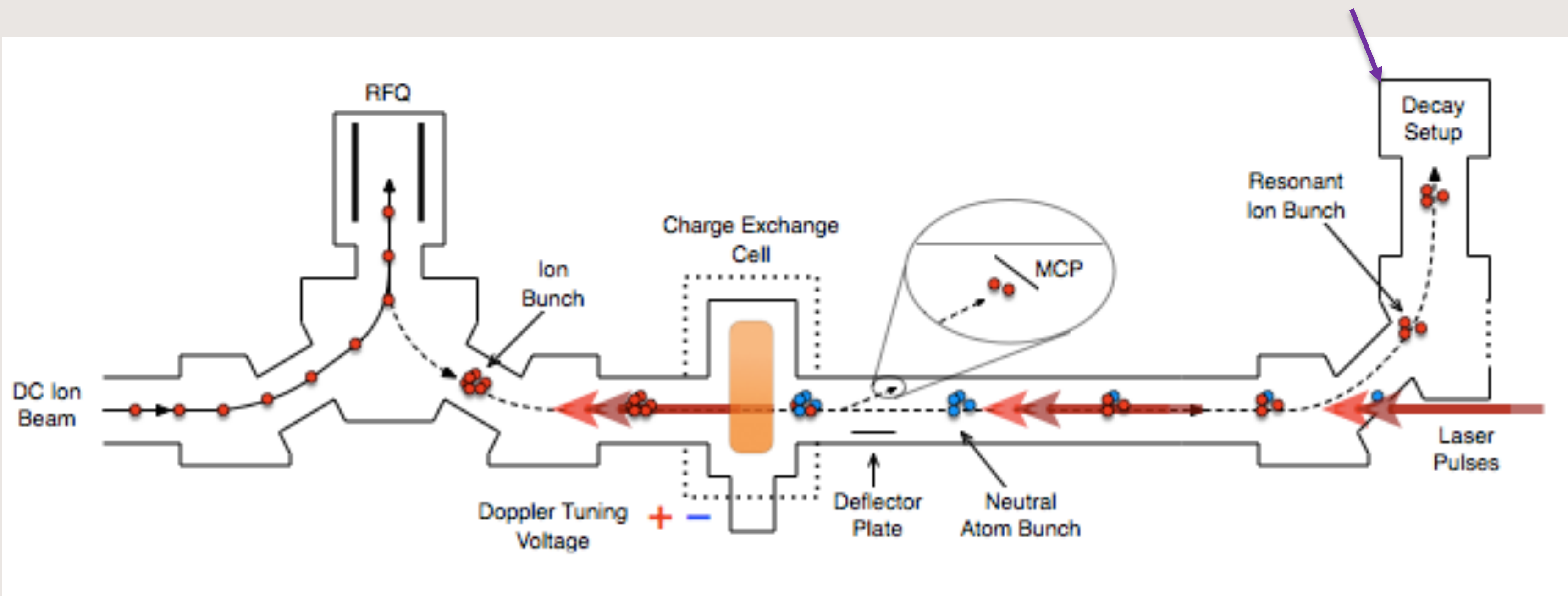


Resonant ionization:

Isomeric/ ground state selectively ionized and then delivered to the decay spectroscopy setup.







Collaborators

TRIUMF

Laser spectroscopy

Matt Pearson

(Staff Scientist)

Andrea Teigelhoefer

(Staff Physicist)

Phil Levy

(Staff Scientist)

Gamma-ray spectroscopy

Adam Garnsworthy

(Staff Scientist)

Shaun Georges

(Mechanical Technician)

Tennessee Technological University

Sean M. Jones

John P. Nelms

Jacob W. Hott

(Undergraduate team)

U.S. DEPARTMENT OF ENERGY | Office of Science

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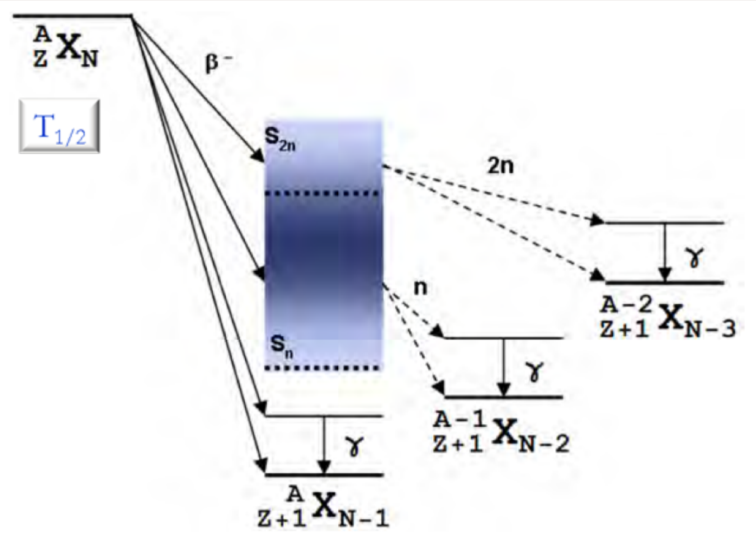
beta decay and gamma de-excitation

- β⁻ decay (Z+1, N-1)

  n → p + e + ν



Rules for beta decay

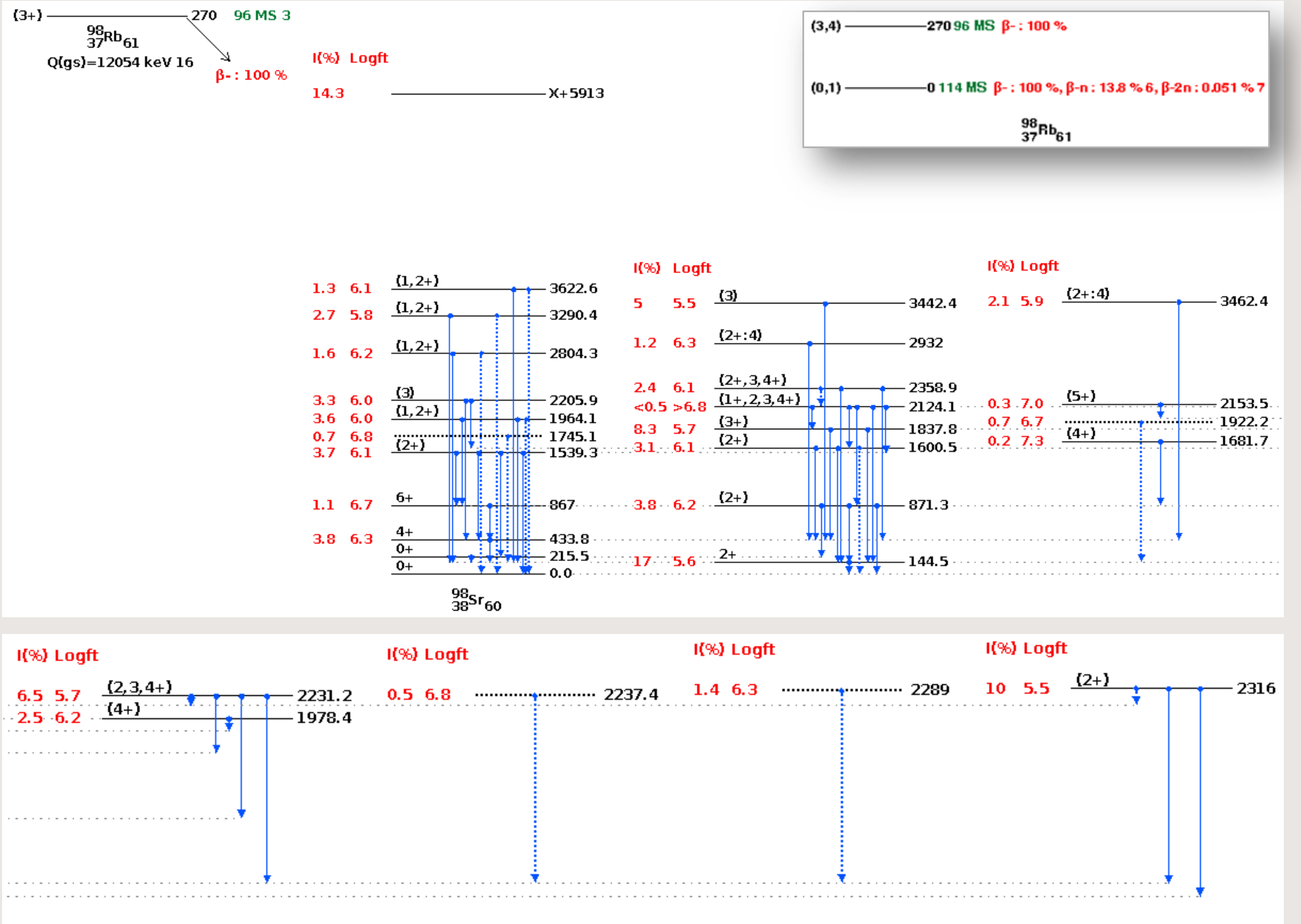
Decay type	Change in parity	Change in angular momentum
F	no	$\Delta J = 0$
GT	no	$\Delta J = 0, \pm 1$

Decay type	ΔJ	ΔT	$\Delta \pi$	log(ft)
Superallowed	$0^+ \to 0^+$	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

Rules for gamma emission

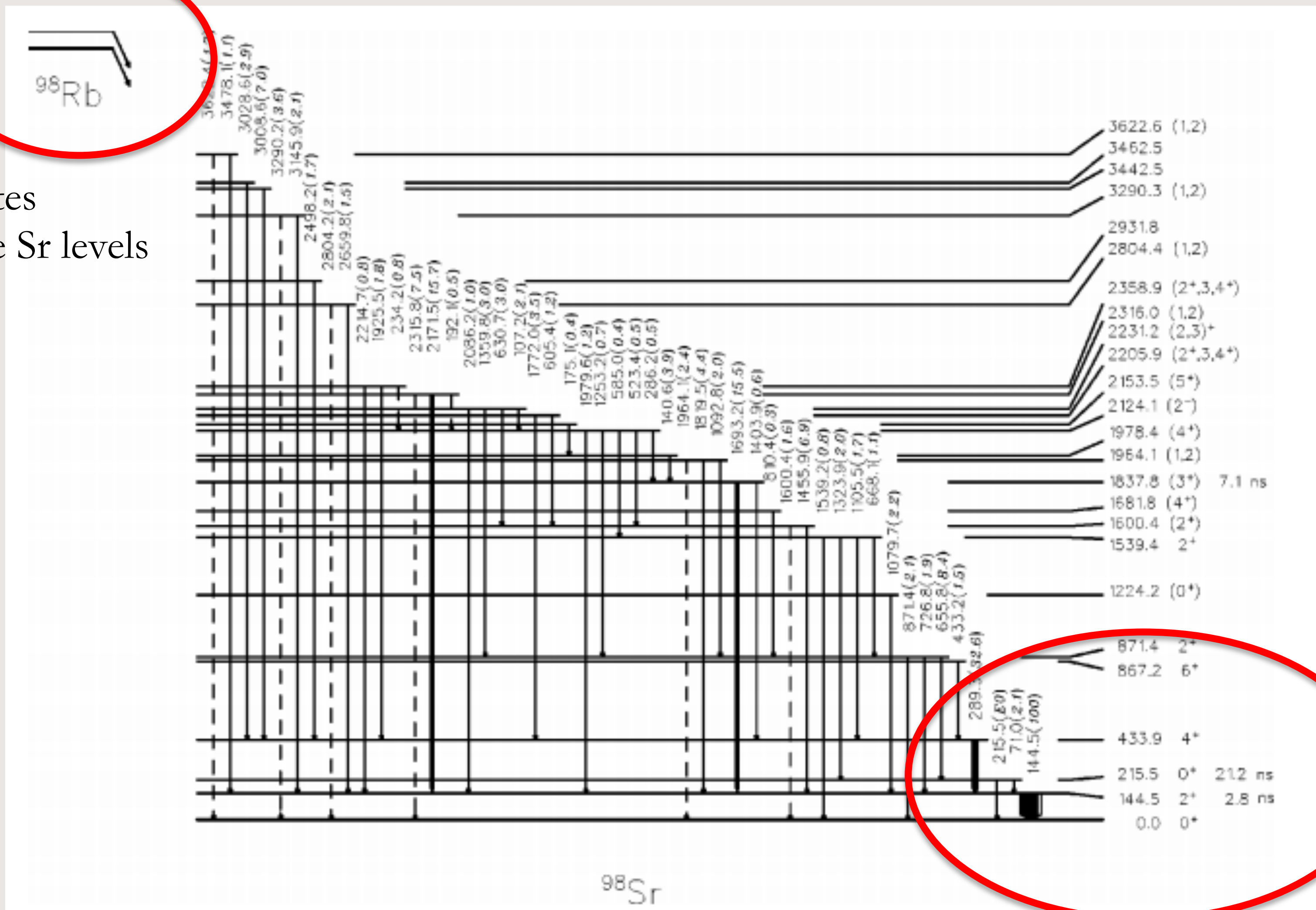
Radiation type	Name	$l = \Delta I$	$\Delta\pi$
E1	Electric dipole	1	Yes
M1	Magnetic dipole	1	No
E2	Electric quadrupole	2	No
M2	Magnetic quadrupole	2	Yes
E3	Electric Octupole	3	Yes
M3	Magnetic Octupole	3	No
E4	Electric hexadecapole	4	No
M4	Magnetic hexadecapole	4	Yes

Conventional decay spectroscopy (β–γ)

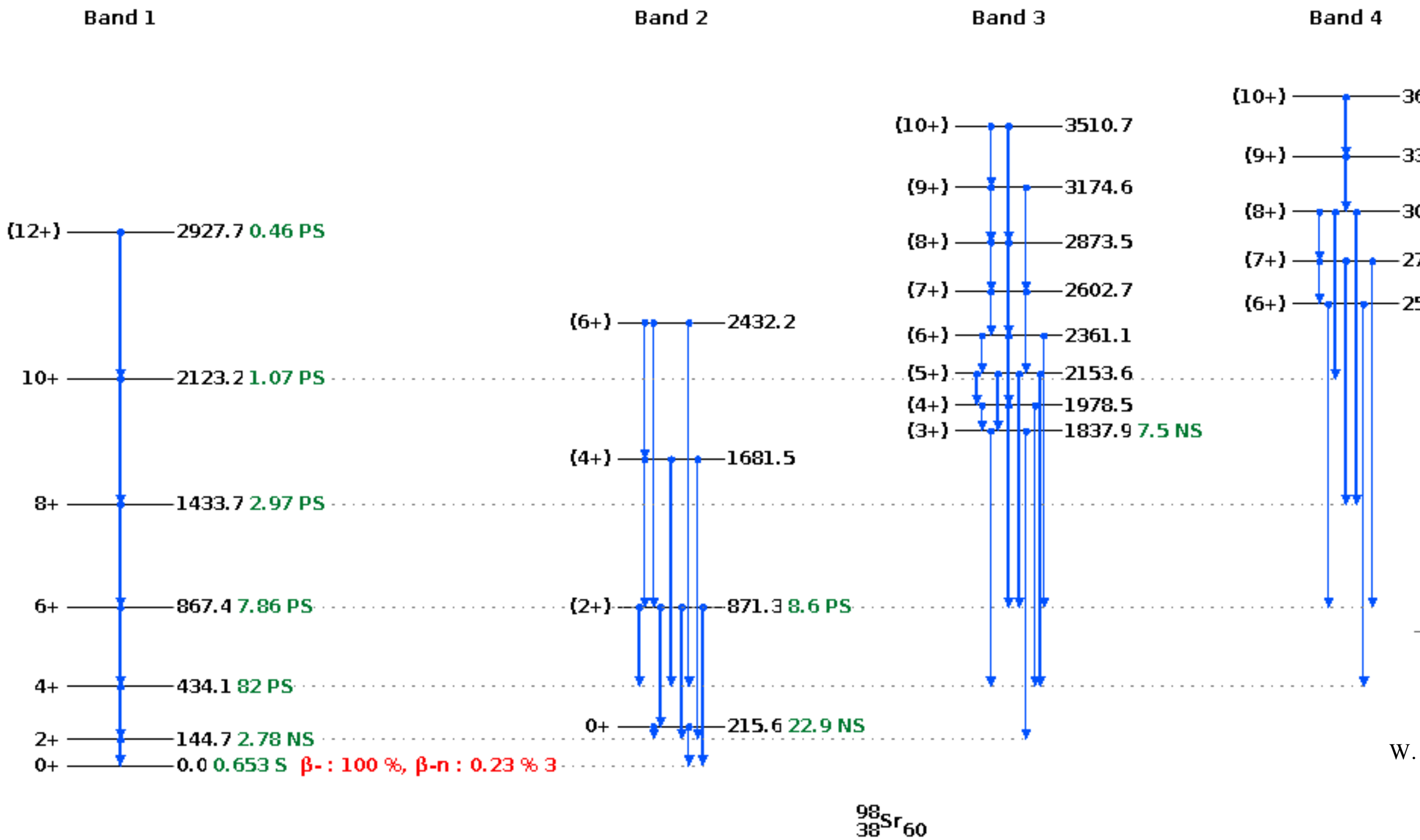


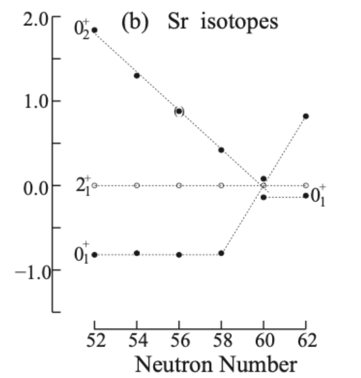
Conventional decay spectroscopy (β–γ)

Two states populate Sr levels



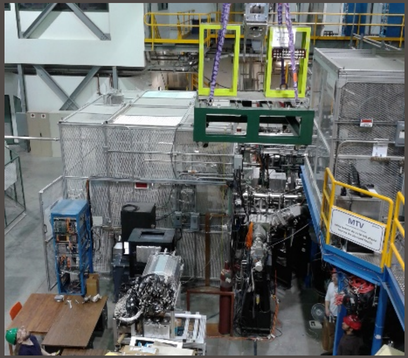
G. Lhersonneau et al. Phys. Rev. C 65 024318 (2002)





W. Urban et. al PRC **99**, 064325 (2019)

Hyperfine structure



Atomic structure

Quantum numbers to describe atomic levels:

Principal quantisation $n = 1, 2, 3,$
Angular momentum $l = 0, \ldots, n - 1$
Magnetic substate $m = -l, \ldots, 0, \ldots, l$

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

Realistic potential:

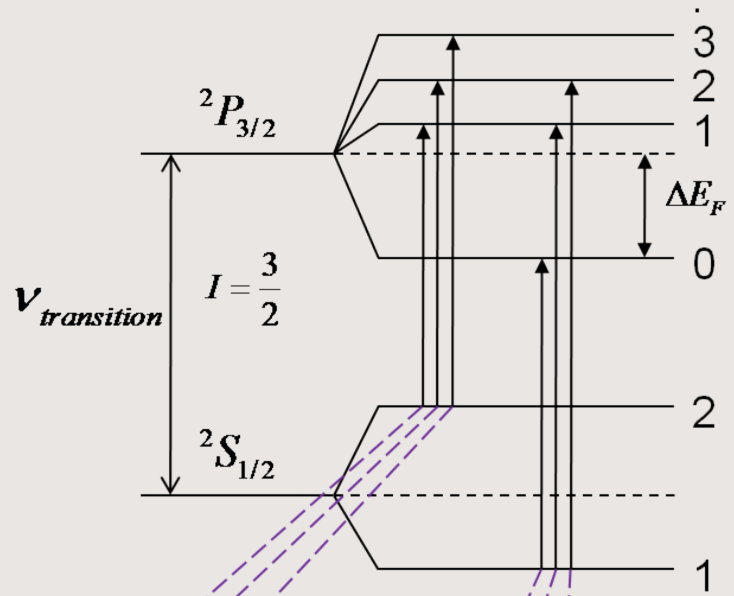
$$V(r) = V_{Coulomb}^{(r-1)} + V_{Dipole}^{(r-3)} + V_{Quadrupole}^{(r-5)} + \ldots$$

Hyperfine interactions

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

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

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

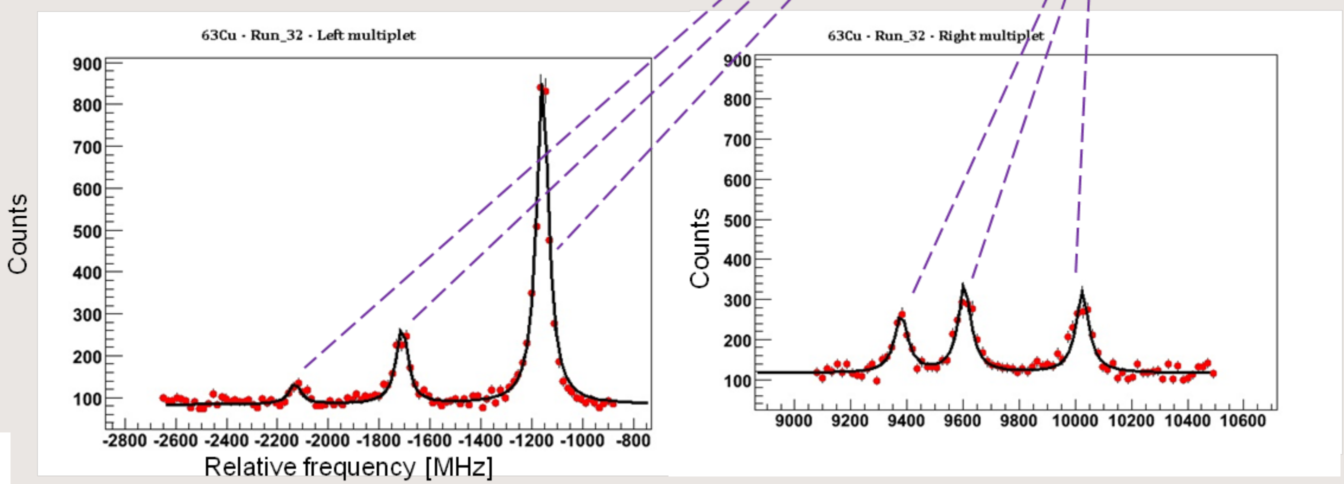


- Magnetic dipole HF parameter:

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

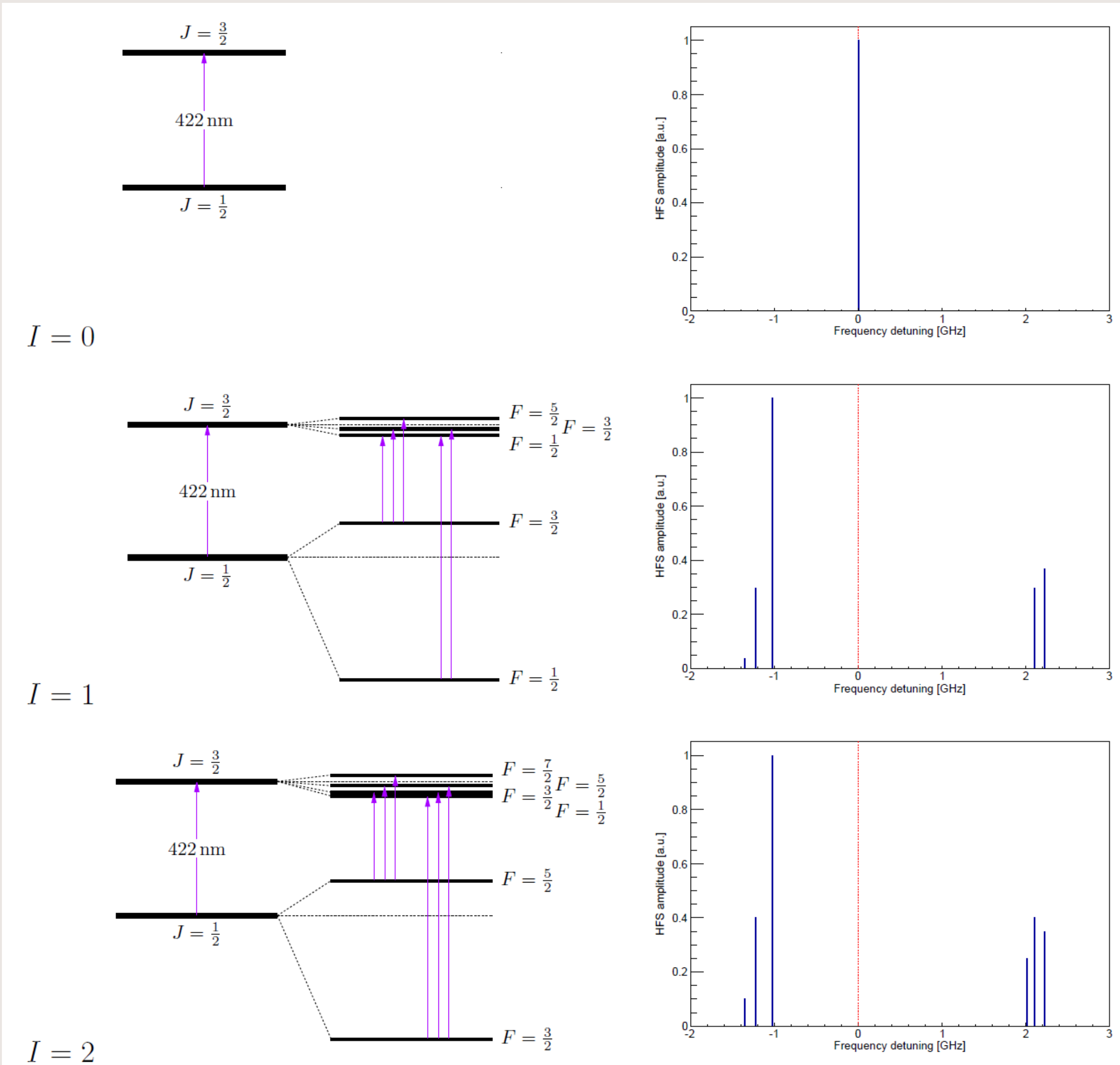
- Electric quadrupole HF parameter:

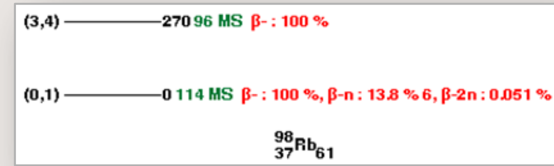
$$B = eQV_{zz}$$



$$\begin{aligned}\Delta l &= \pm 1\\ \Delta J &= 0, \pm 1, \quad J = 0 \nrightarrow 0\\ \Delta F &= 0, \pm 1, \quad F = 0 \nrightarrow 0\end{aligned}$$

^{98}Rb – hyperfine structure





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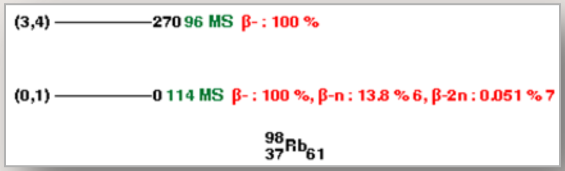
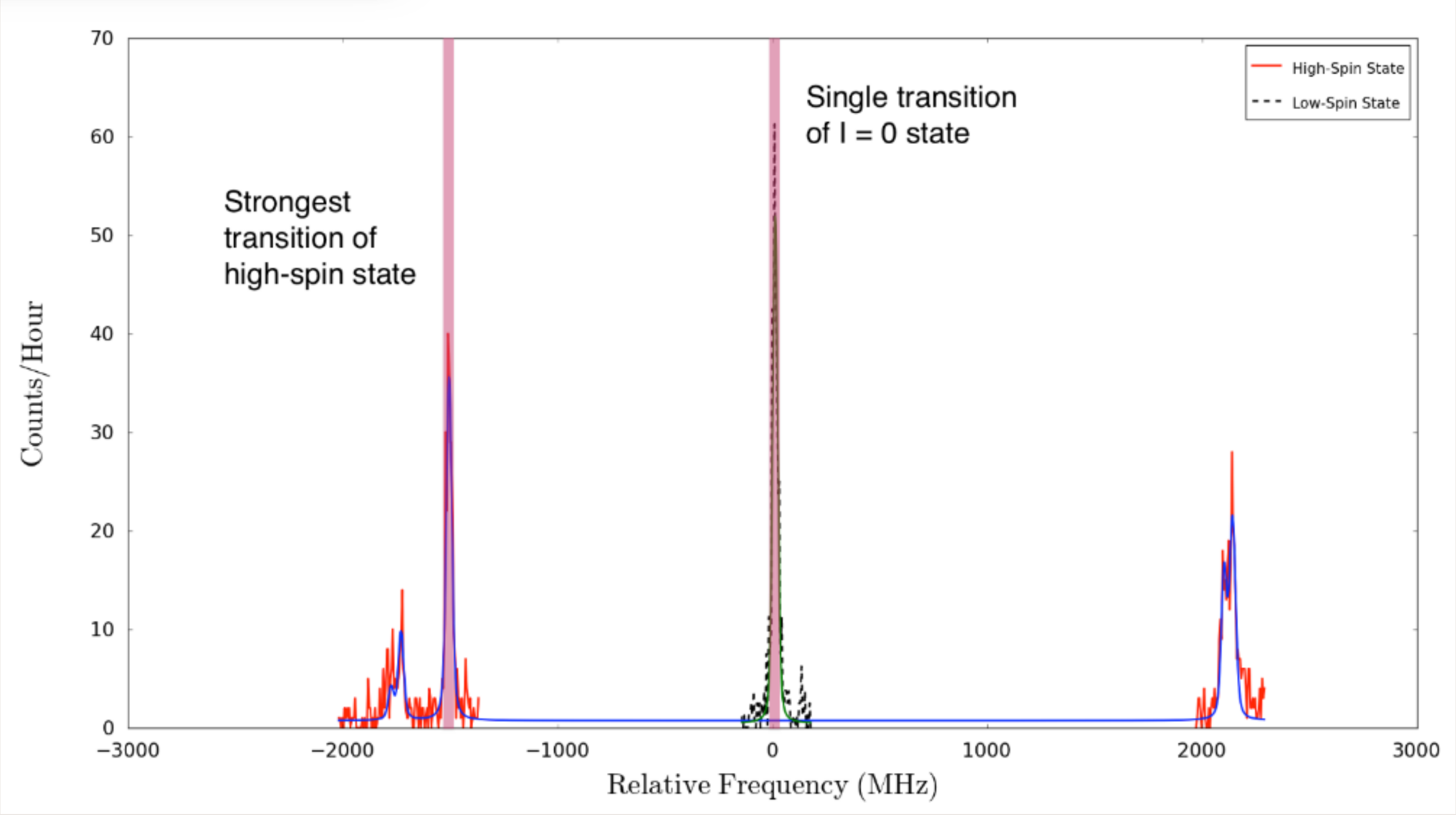
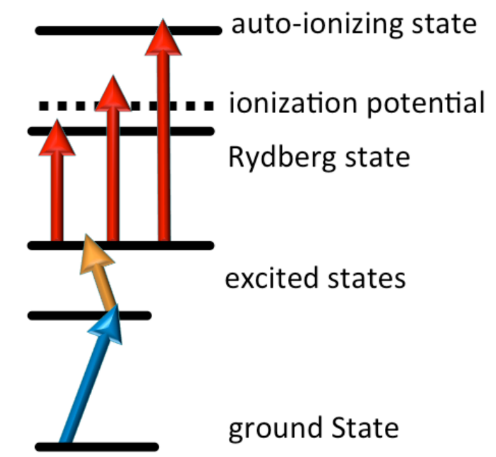




Description of Experiment



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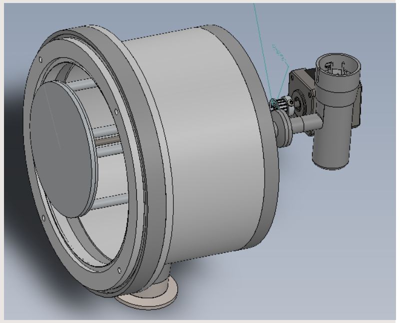
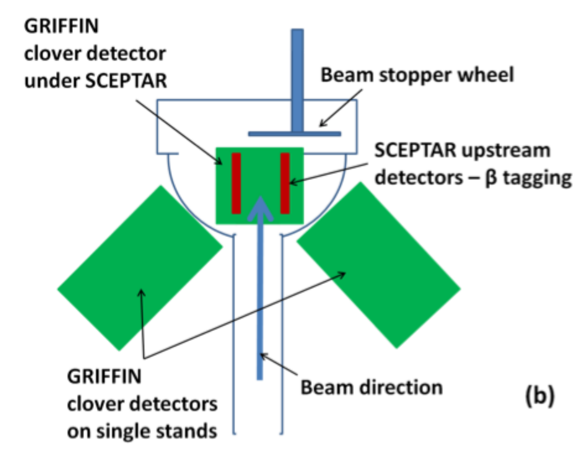
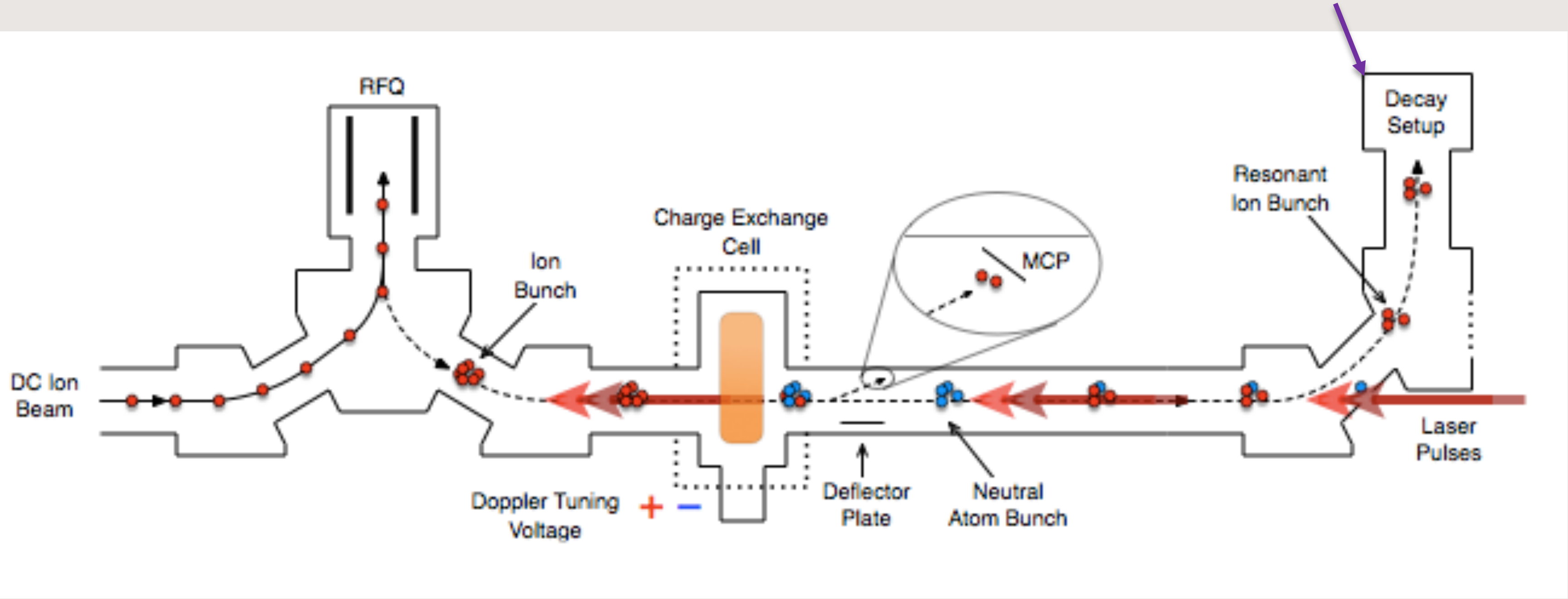
Isomeric/ ground state selectively ionized and then delivered to the decay spectroscopy setup.







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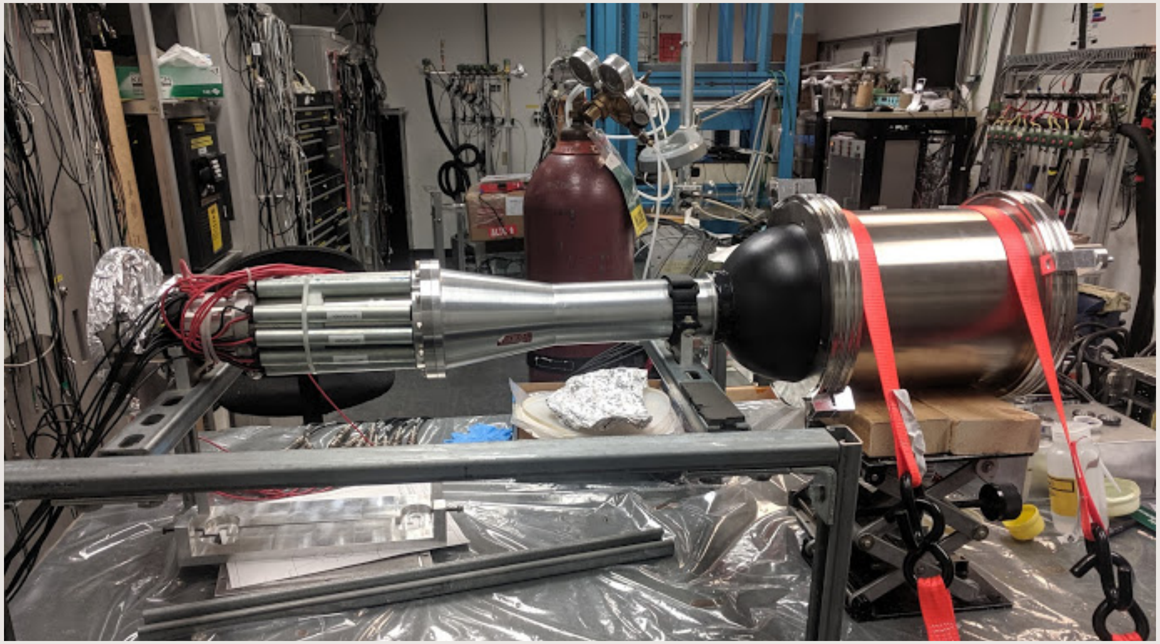
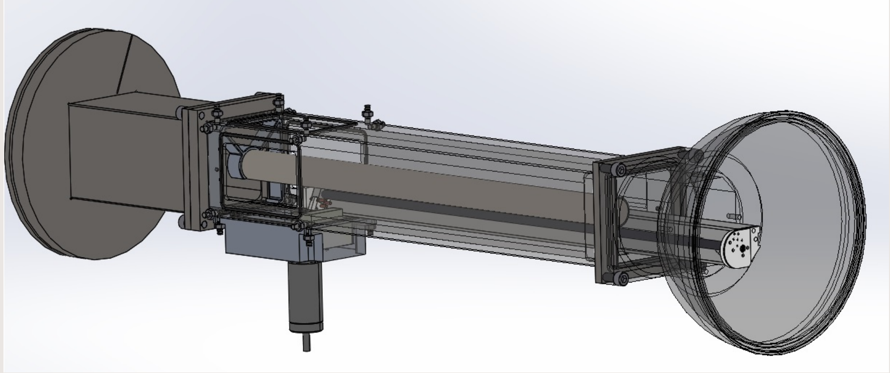
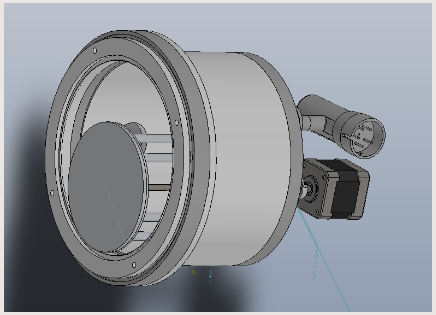
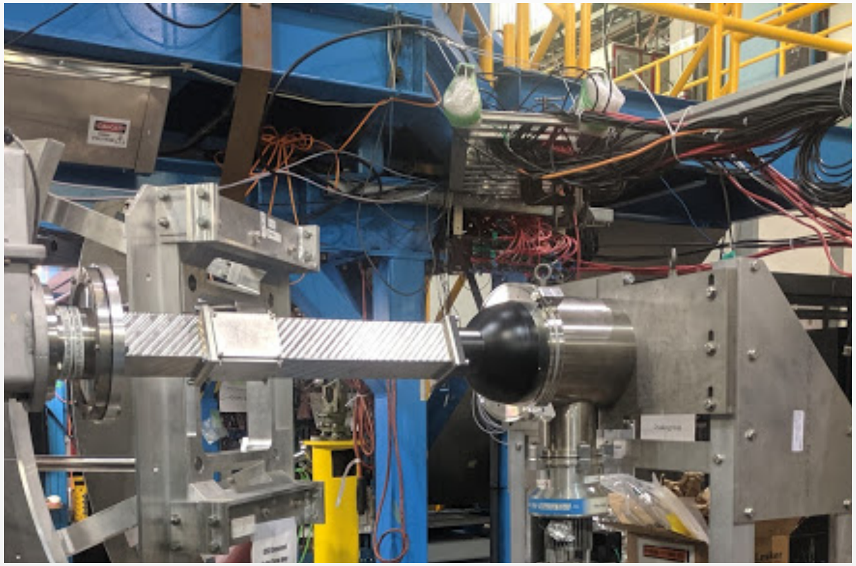
Beta-detection development

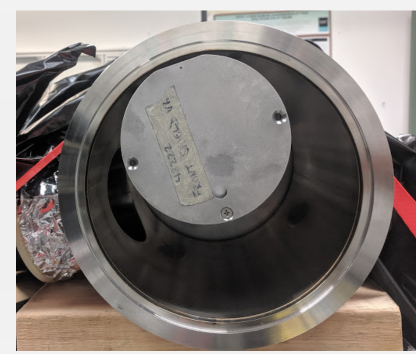






Decay station



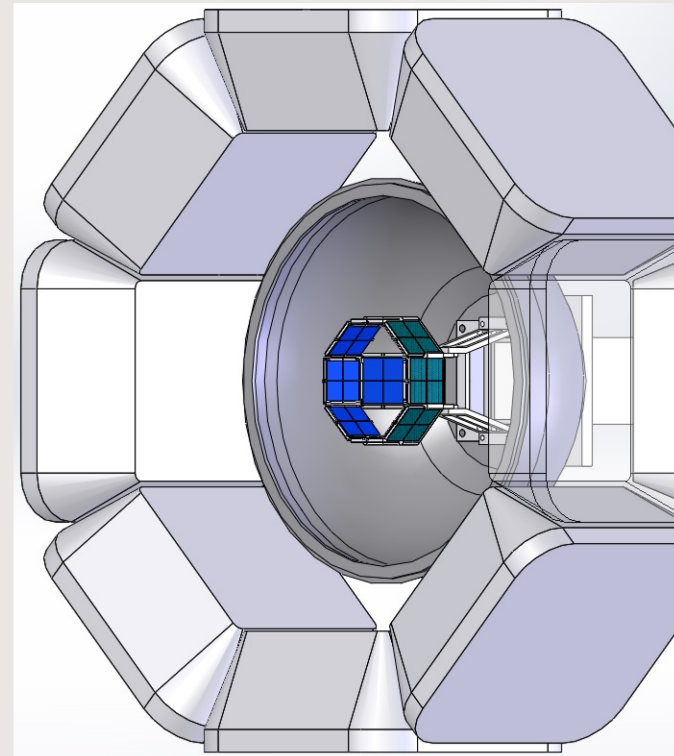


Ancillary detector for Rare Isotope Event Selection (ARIES)

A major upgrade of the SCEPTAR beta-tagging array for GRIFFIN

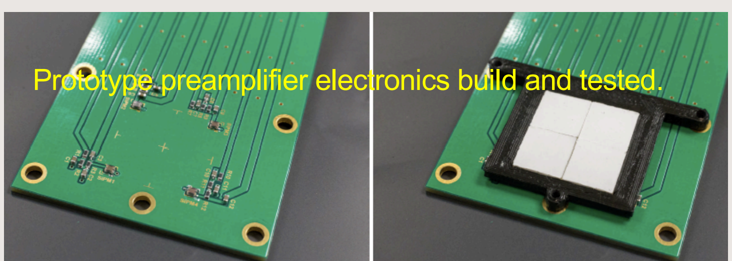
New ARIES beta-tagging array enables:

- Counting of high source activities ~20MBq with ~90% solid-angle coverage.
- Beta-gamma angular correlations with >50 unique angles.
- Beta-gamma fast coinc. timing (few ps) with $LaBr_3$(Ce) detectors (x2 eff. increase over ZDS).
- Easy and economical replacement of detectors contaminated with long-lived activity.

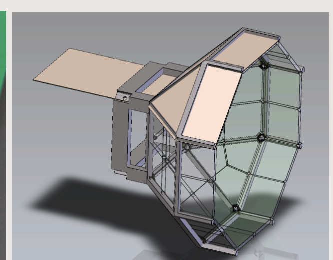


Geometry optimized for GRIFFIN with 1 beta paddle for each HPGe crystal, + 8 triangles + 4 downstream = (36 US)+(40 DS) = 76 total channels

- 1.5mm thick BC422Q ultra-fast plastic scintillator.
- Laser-etching to optically-segment scintillators and prevent light loss.
- Light read-out using SiPM sensors printed on flexible circuit board ~50µm thickness and held in place with a 3D-printed support structure will provide energy and fast-timing signal.
- Processing using 500MHz, 12-bit digitizers in the GRIFFIN DAQ.



Prototype preamplifier electronics build and tested.



Victoria Vedia, Rashmi Umashankar, Adam Garnsworthy, Max Winokan, Kurtis Raymond Miles Constable,
Daryl Bishop (Electronics design),
Shaun Georges (Mechanical design)

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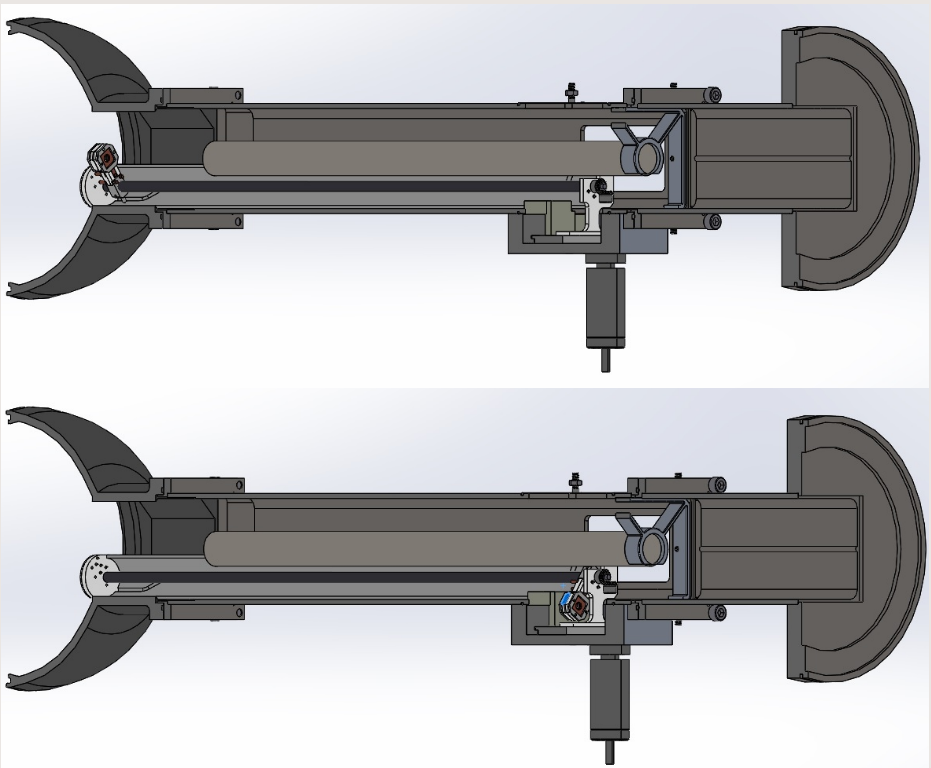
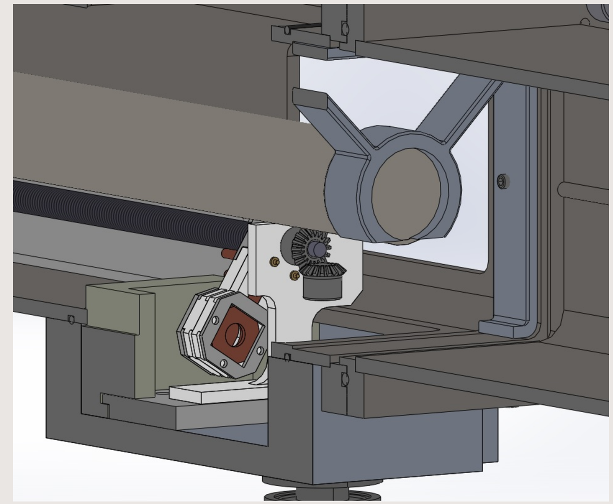
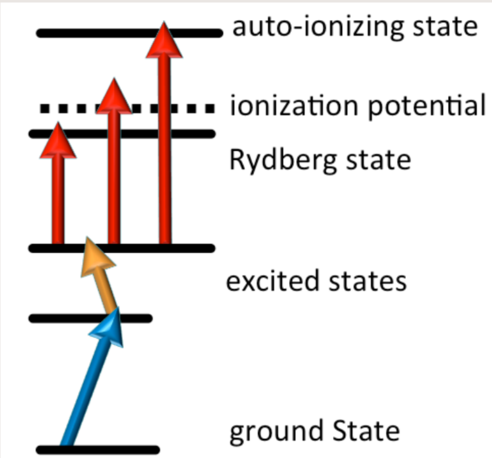
Beam monitoring



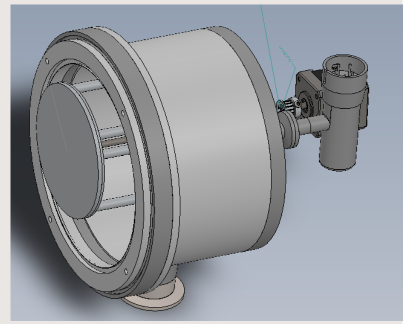


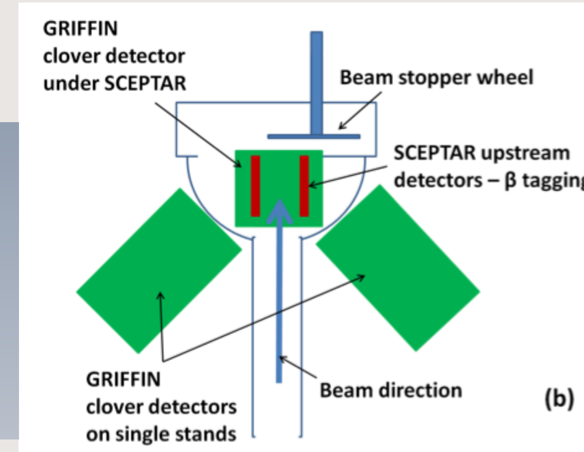
Description of Experiment

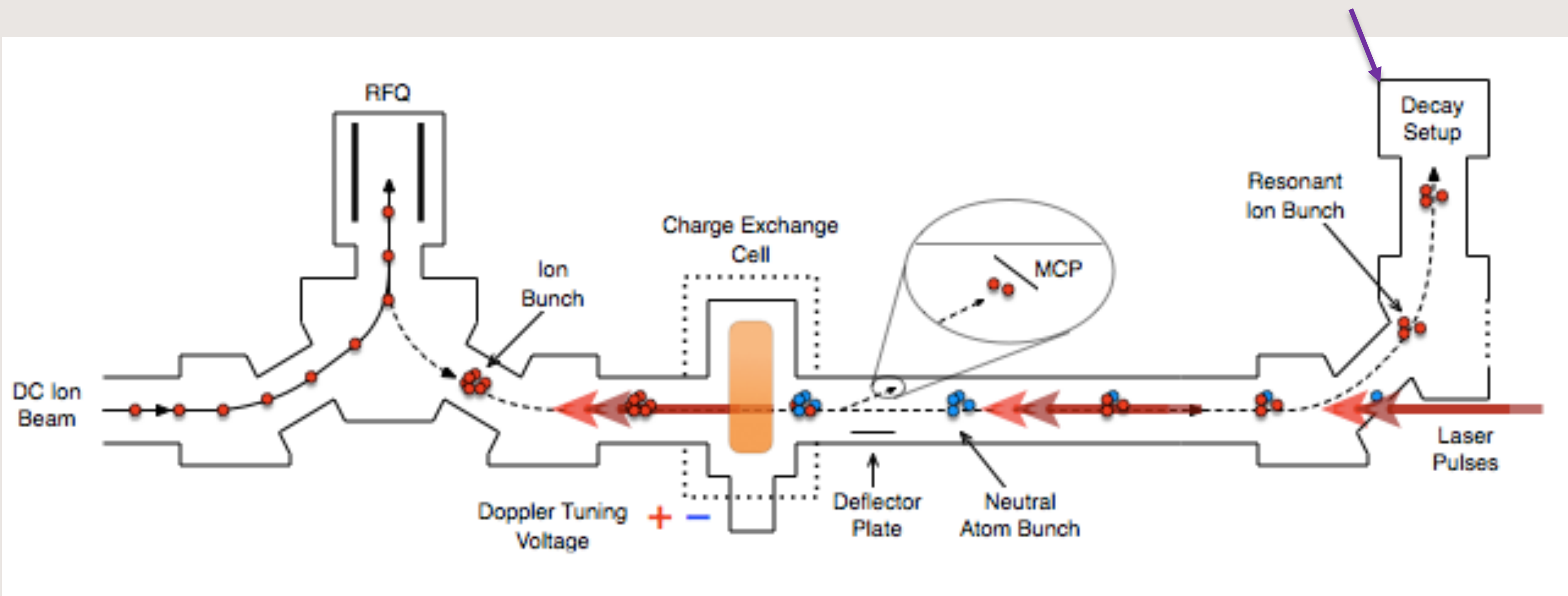


Resonant ionization:

Isomeric/ ground state selectively ionized and then delivered to the decay spectroscopy setup.



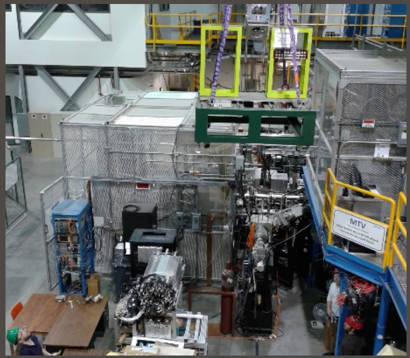




Resonant Ionization

(using high resolution at the first step of selectivity)

For decay-spectroscopy

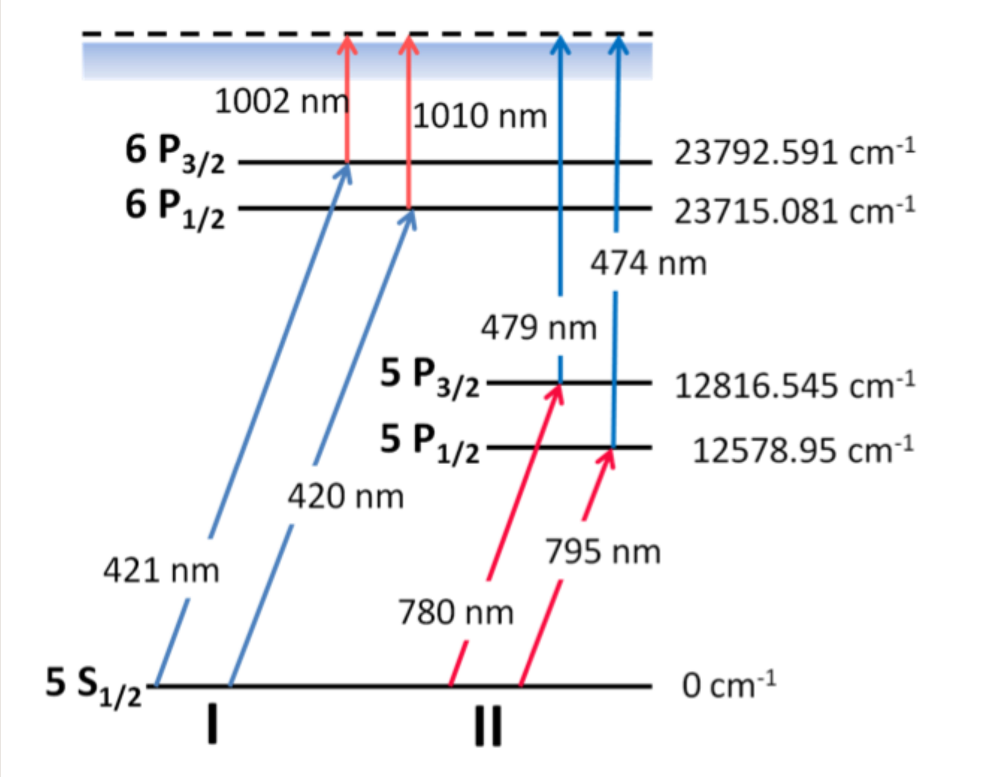


Description of Experiment

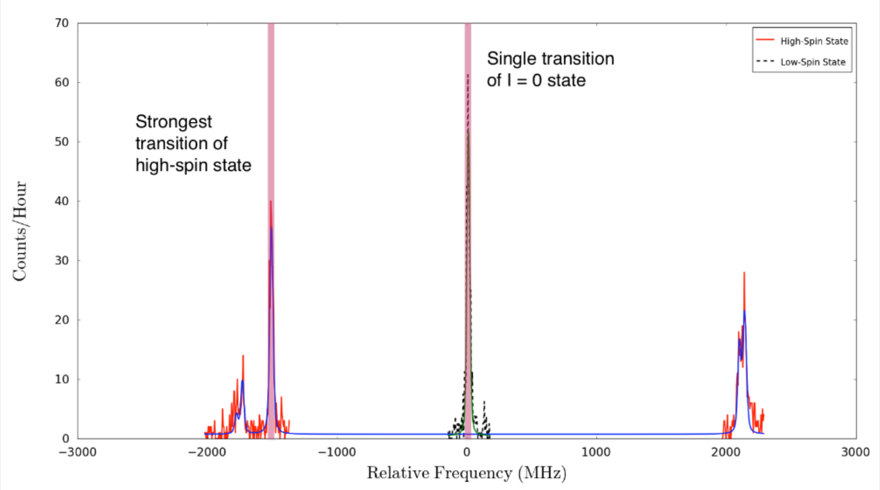
Ionization schemes:

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.



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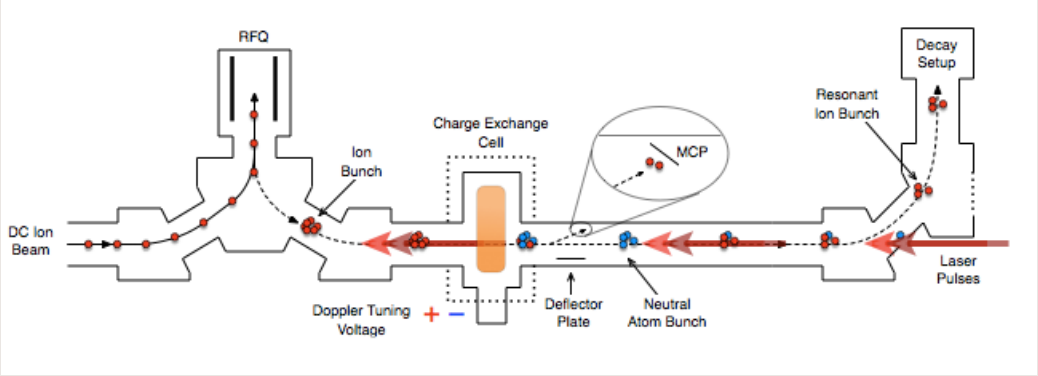
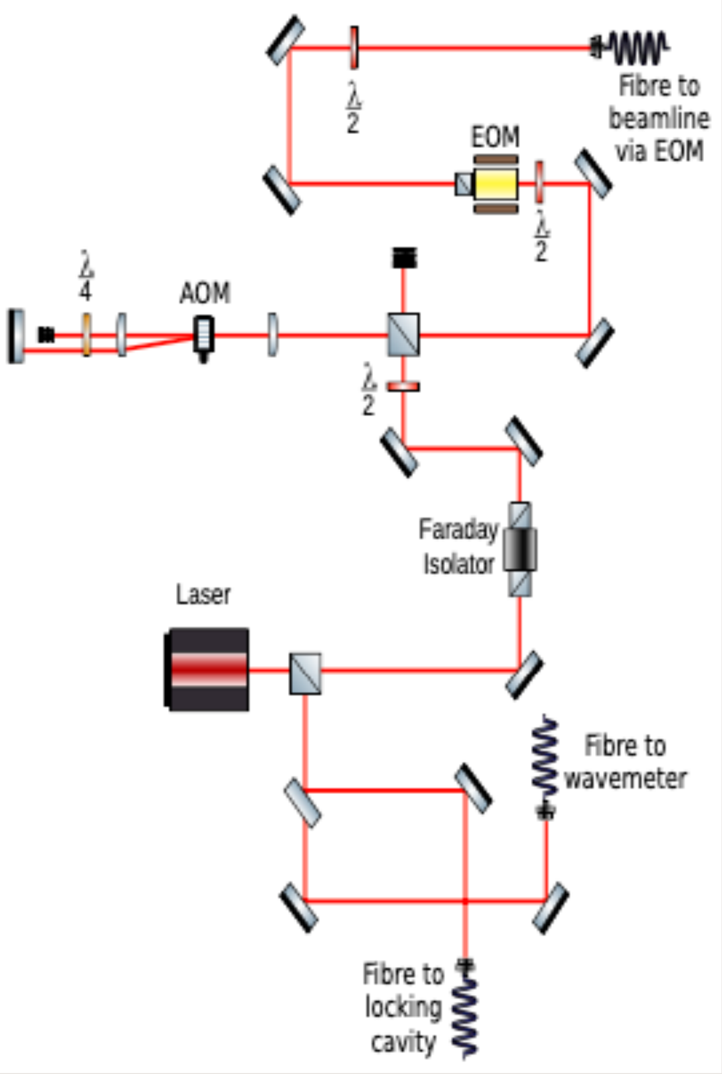
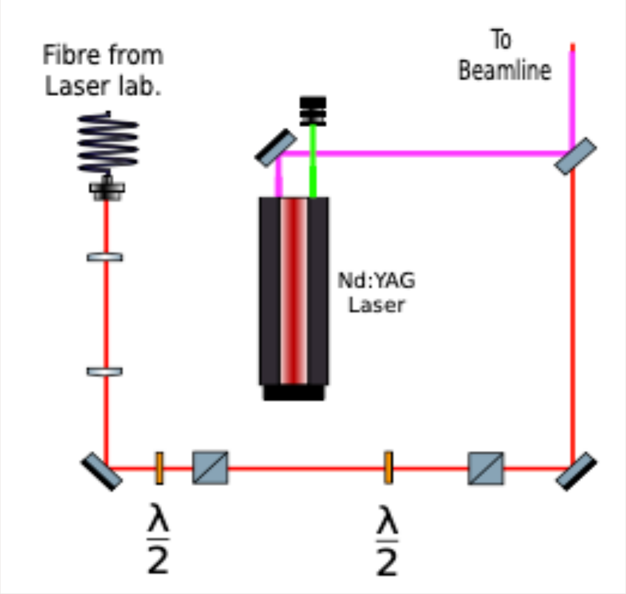
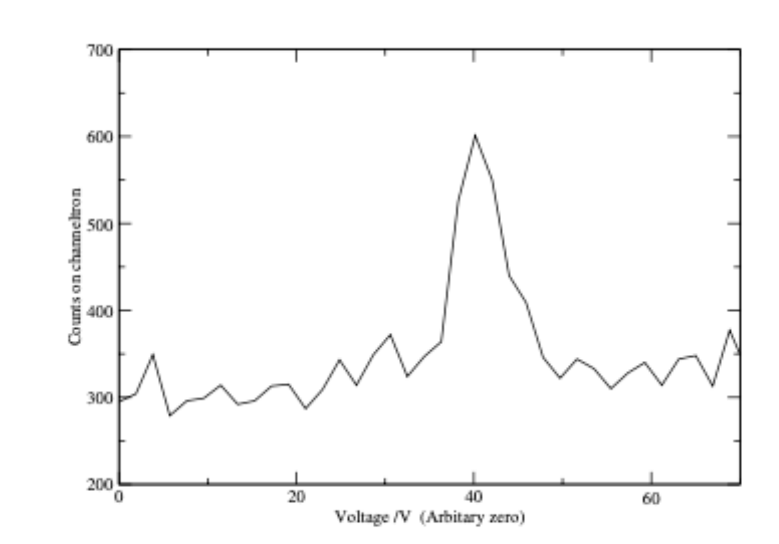
Development of resonant ionization setup

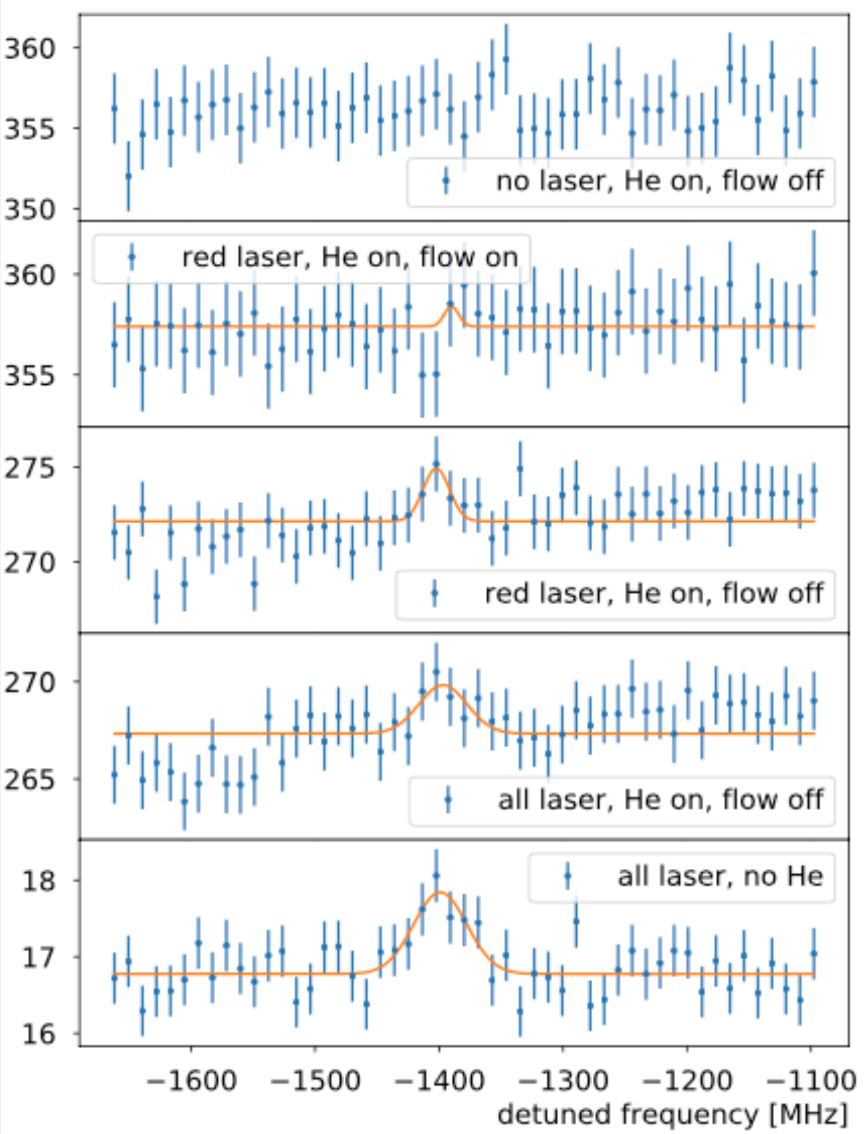






Results of reionization





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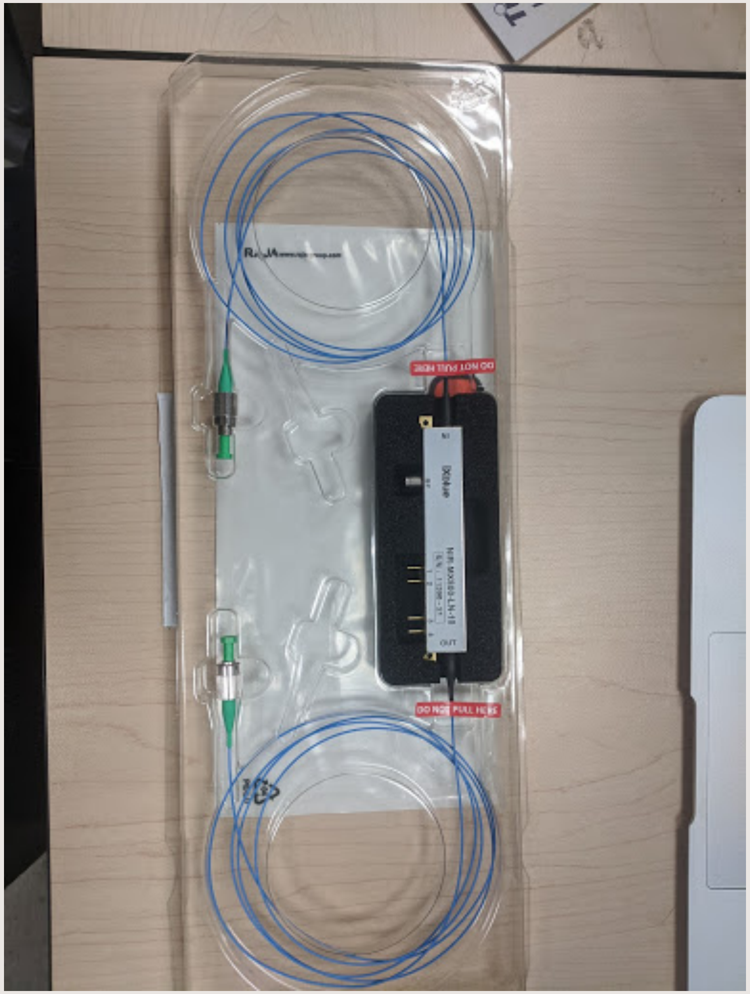
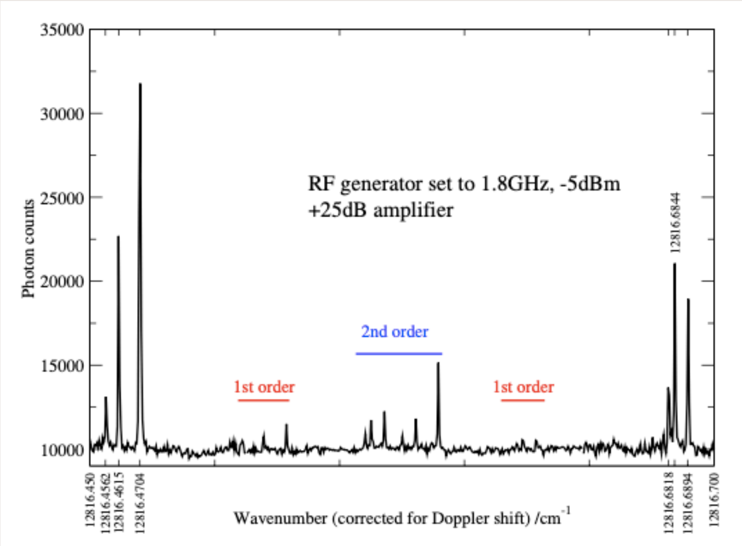
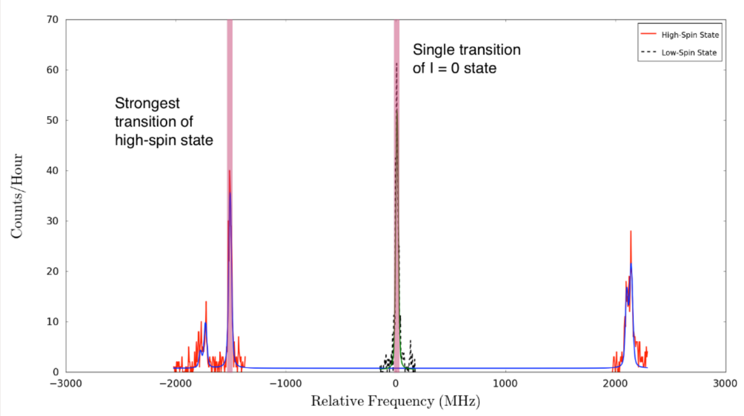






Pros and cons

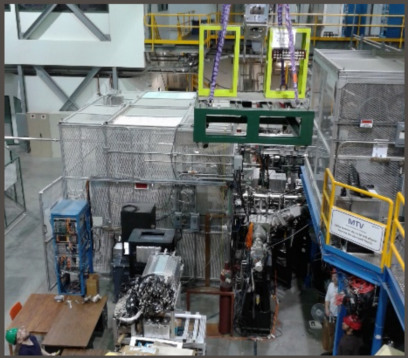
- What do we gain?
  - Beam purification
  - Detailed feeding from ground and isomeric states

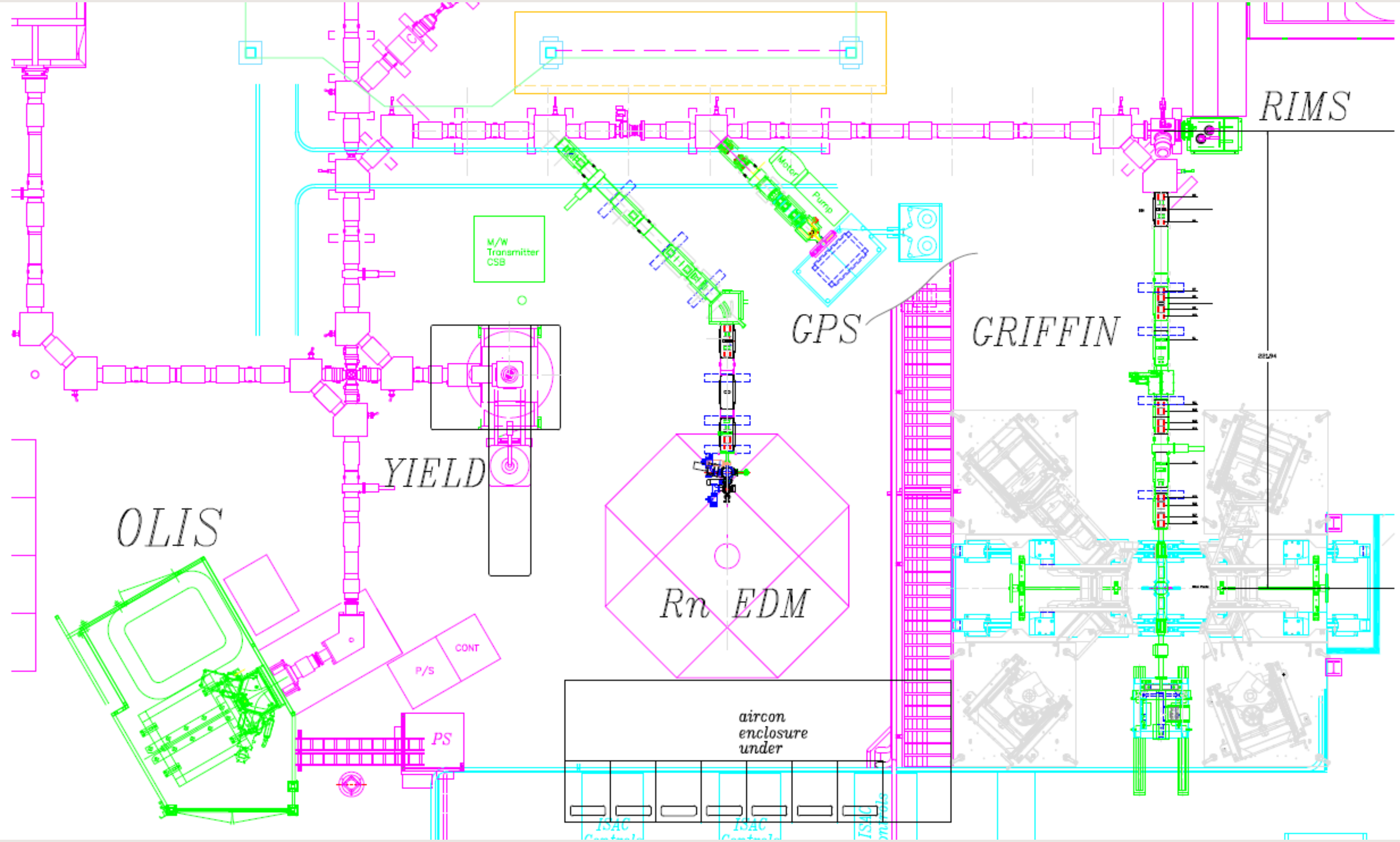
    OR
  - Detailed feeding from a particular isotope
  - Hyperfine structure
    - Spin of ground state (and possible excited isomeric states)
    - Magnetic moments and maybe static quadrupole moment

- 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

POLARIS

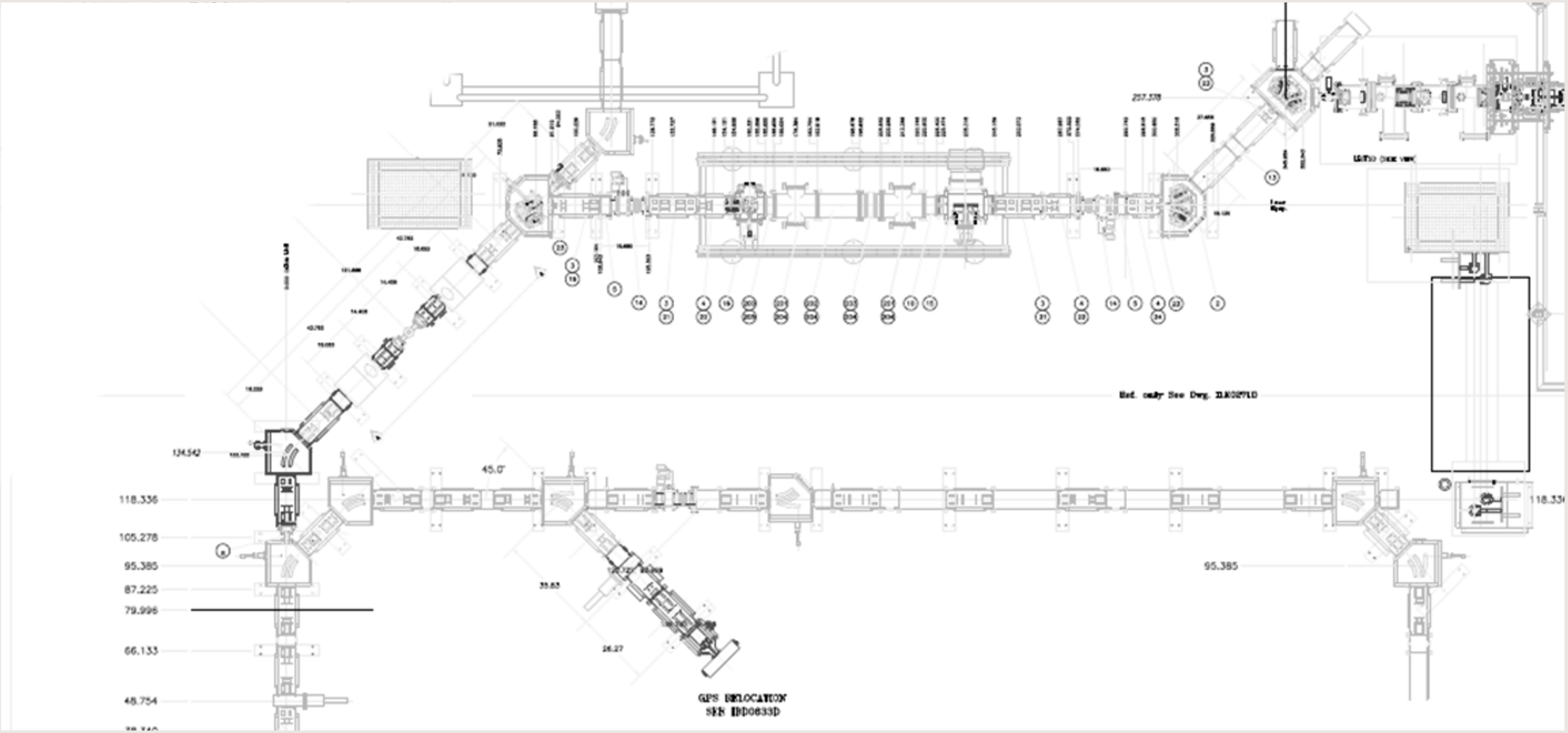
Polarised Radioactive Isotope Science at TRIUMF





RIMS
M/W
Transmitter
CSB
Motor
Pump
GPS
GRIFFIN
YIELD
OLIS
Rn EDM
CONT
P/S
PS
aircon
enclosure
under
ISAC
ISAC
ISAC

The idea:
Join the polarizer beam line to GRIFFIN



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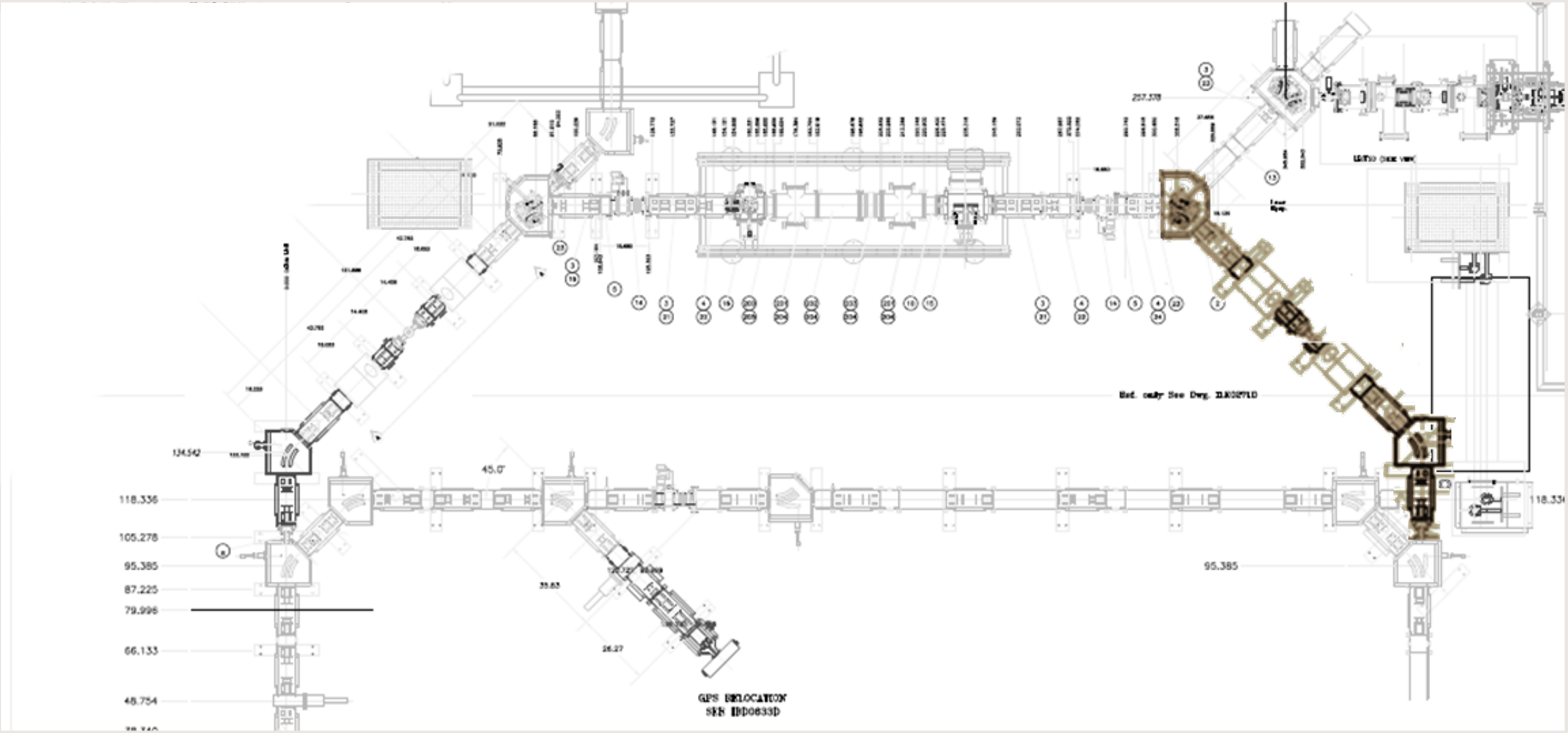

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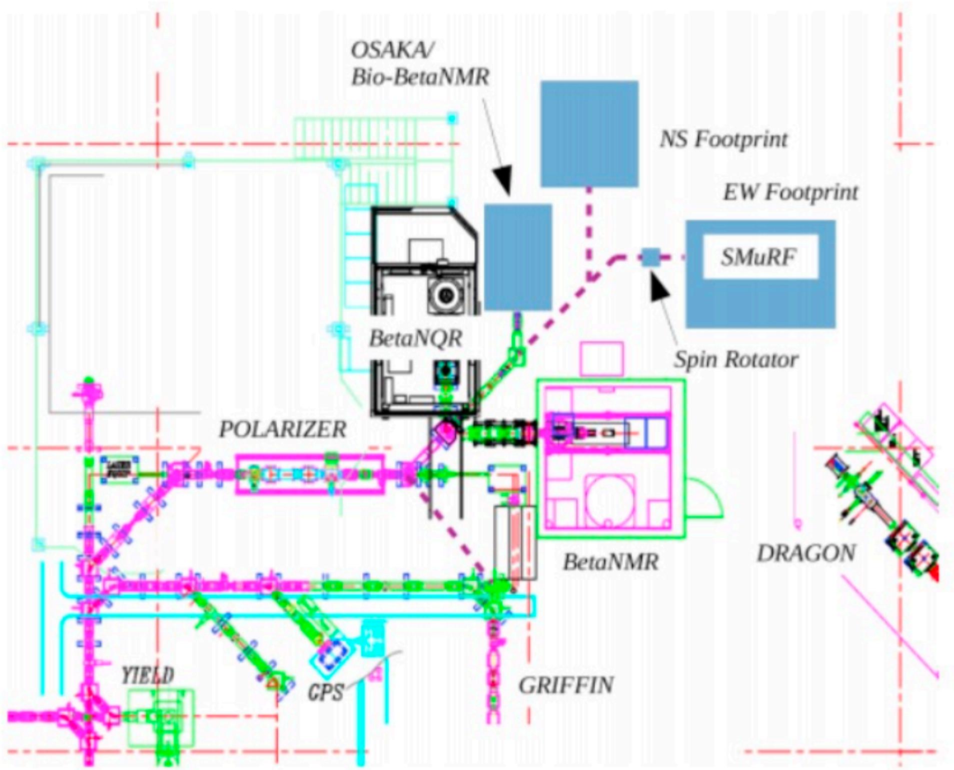
TRIUMF

Proposed Layout in ISAC-1 Hall



OSAKA / Bio-BetaNMR :
dedicated β-NMR spectrometer for liquids and high vapour pressure applications, focussing on systems of biochemical and medical relevance; chemical Shift Measurements by ^{31}Mg, ^{54}Cu, ^{74}Cu, ^{75}Cu, ^{230}Ac, ^{232}Ac β-NMR

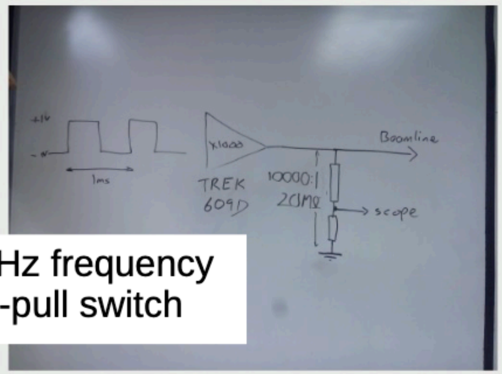
North South Footprint : Nuclear Structure and Symmetry
2x2.5 m footprint for modular experiments including resonant ionisation decay-spectroscopy;

East West Footprint : Physical Science
dedicated 2.5x3 m high voltage platform, 0.1-30 keV ions
radio frequency spin echo and adiabatic inversion
vector magnet (0-2 Tesla || beam, 0-0.5 Tesla ⊥ beam)
1.5-300 K closed cycle cryostat

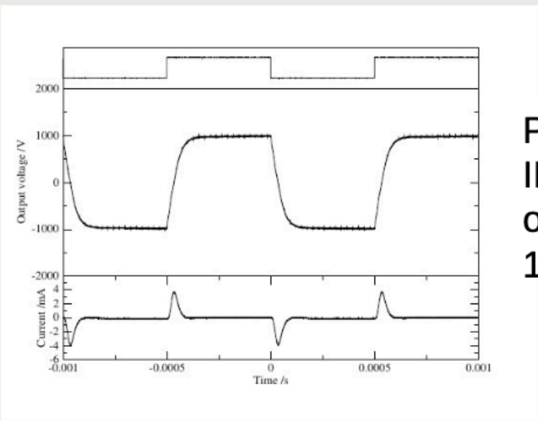
GRIFFIN : Nuclear Structure and Symmetry
3 m low energy polarised beam transport

POLARIZER beamline and Laser Upgrade

Rapid Switching of Beam and Helicity
Quasi continuous Beam on Three Channels

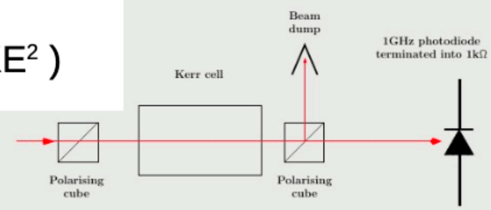


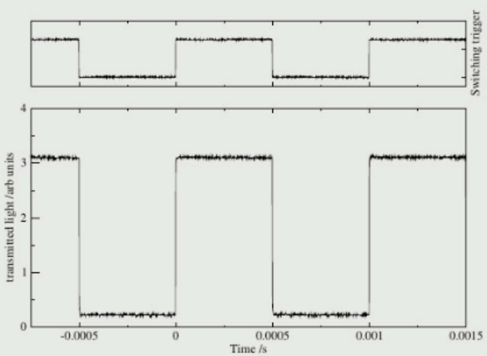
Rapid switching at kHz frequency using Trek HV push-pull switch



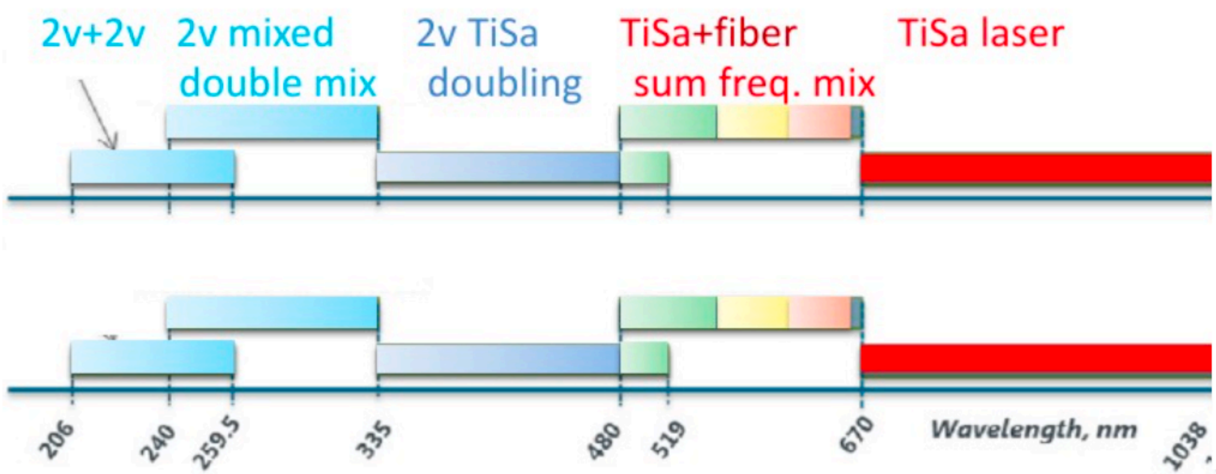
Proposed set-up identical to ILT:YCB3 plates into and out of TITAN. Routine pulsing at > 1kHz with 50:50 duty cycle

Kerr cell: birefringence under application of electric field ($\Delta n = \lambda K E^2$)





New Capabilities with Second Generation Lasers



polarizer upgrade: floating re-ionization cell to avoid beam optics re-tune when changing beam energy change

new spectroscopy chamber section for rapid re-configuration guide field coils

2x cw TiSa laser
2x fiber laser
2x sum freq. mixing
2x double mixed
2x freq. doubling => 1x (2v +2v)
diagnostics, optics & opto-mechanics for beam delivery

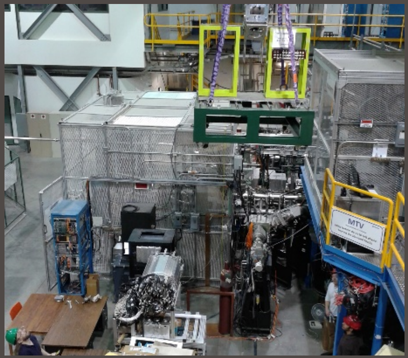
new capabilities:

λ-system polarization
for POLARIS beams: Ac, Al, Ag, Cu, Zn beams

J. Lassen, R. Li and P. Levy | TRIUMF Accelerator Division

Tennessee TECH

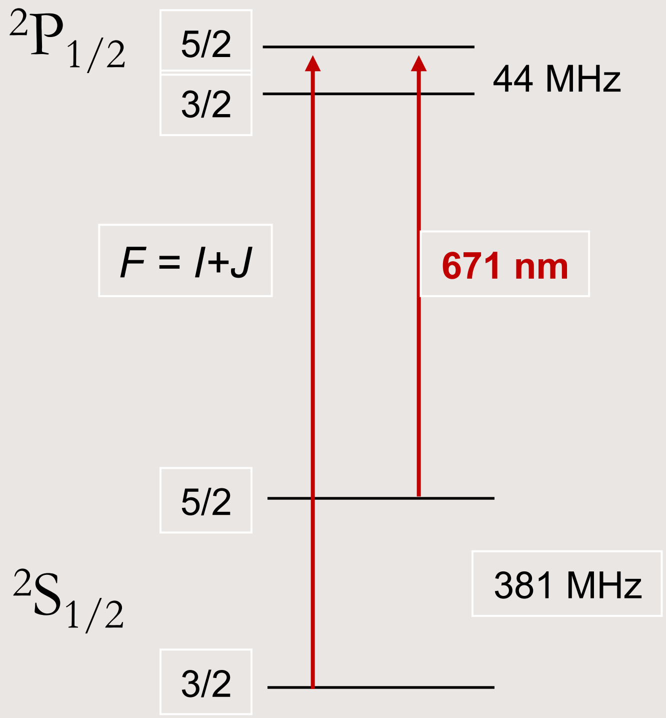
Use of polarized beams for decay spectroscopy

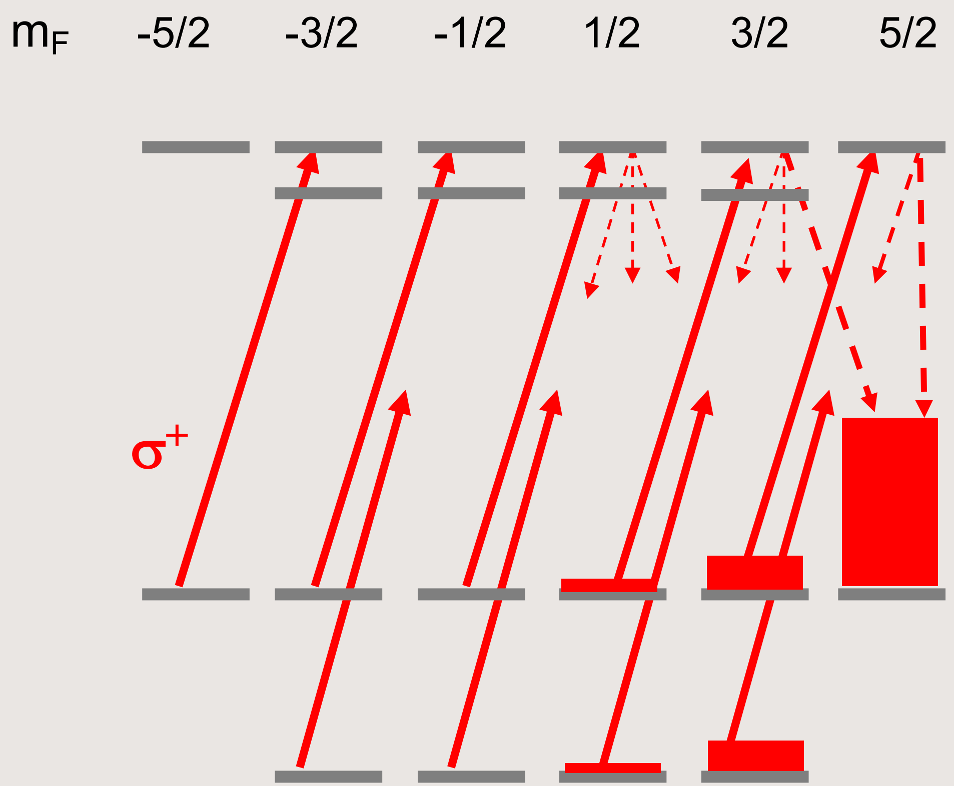


Tennessee TECH

Polarization from optical pumping of ^{8}Li atoms

Hyperfine structure



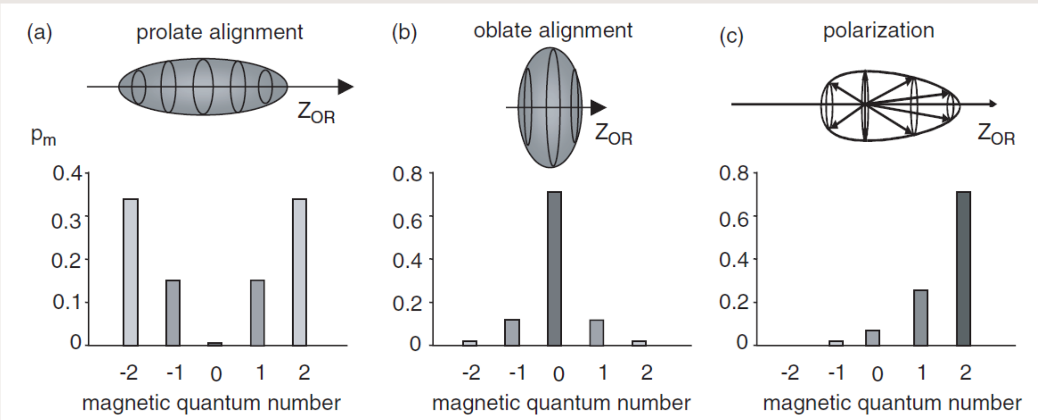


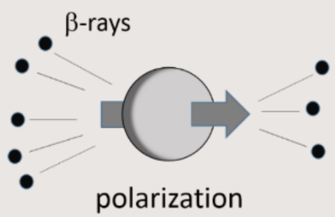
...showing magnetic substates

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

Tennessee TECH

Decay spectroscopy (β–γ) of polarized nuclei





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

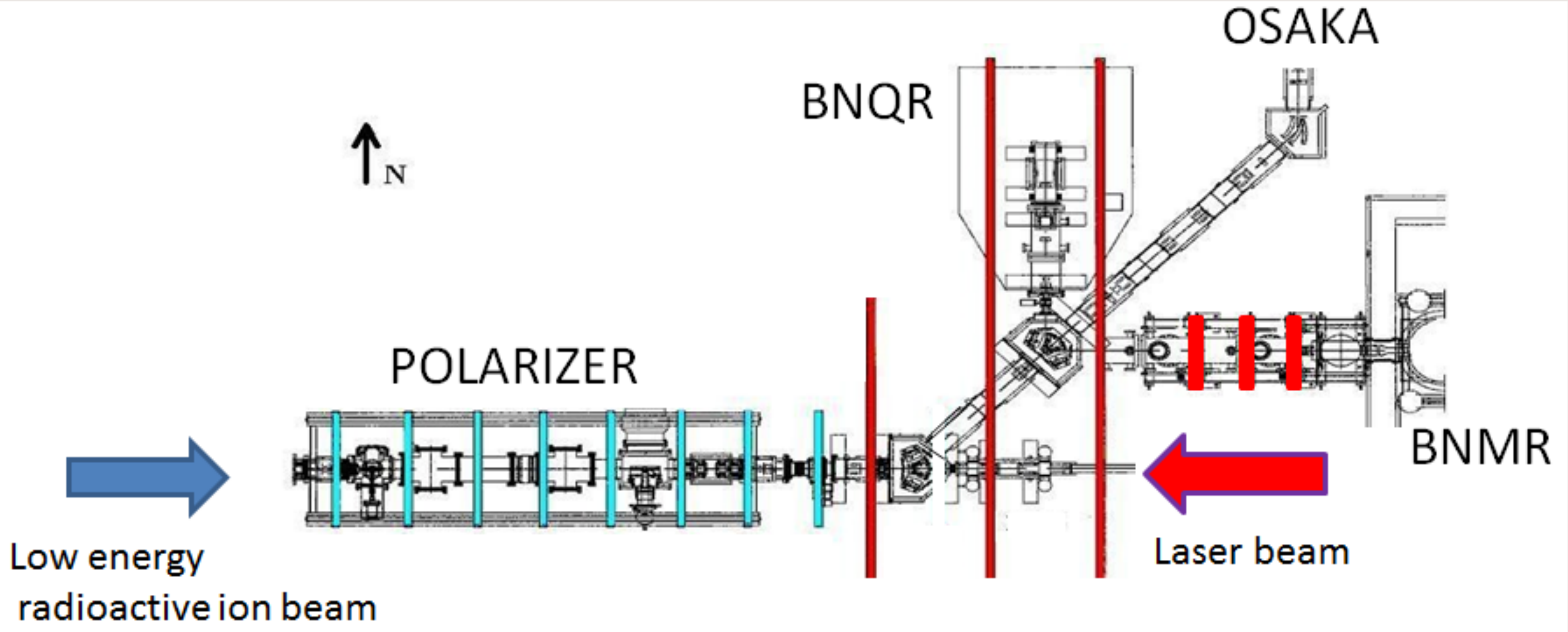
$$A \begin{cases} = -1 & (I_f = I_i - 1), \\ \backsimeq \dfrac{-1}{I_i + 1} & (I_f = I_i), \\ = \dfrac{I_i}{I_i + 1} & (I_f = I_i + 1). \end{cases}$$

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

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

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.

Shape coexistence in neutron-rich ^{31}Mg investigated by β–γ spectroscopy of spin-polarized ^{31}Na

Hiroki Nishibata

Nuclear Spectroscopy Laboratory, RIKEN

- Unique method to assign spin-parity of excited levels based on β–γ spectroscopy of spin-polarized Na isotopes.
- Investigation of excited states of neutron-rich ^{31}Mg (Z=12, N=19)

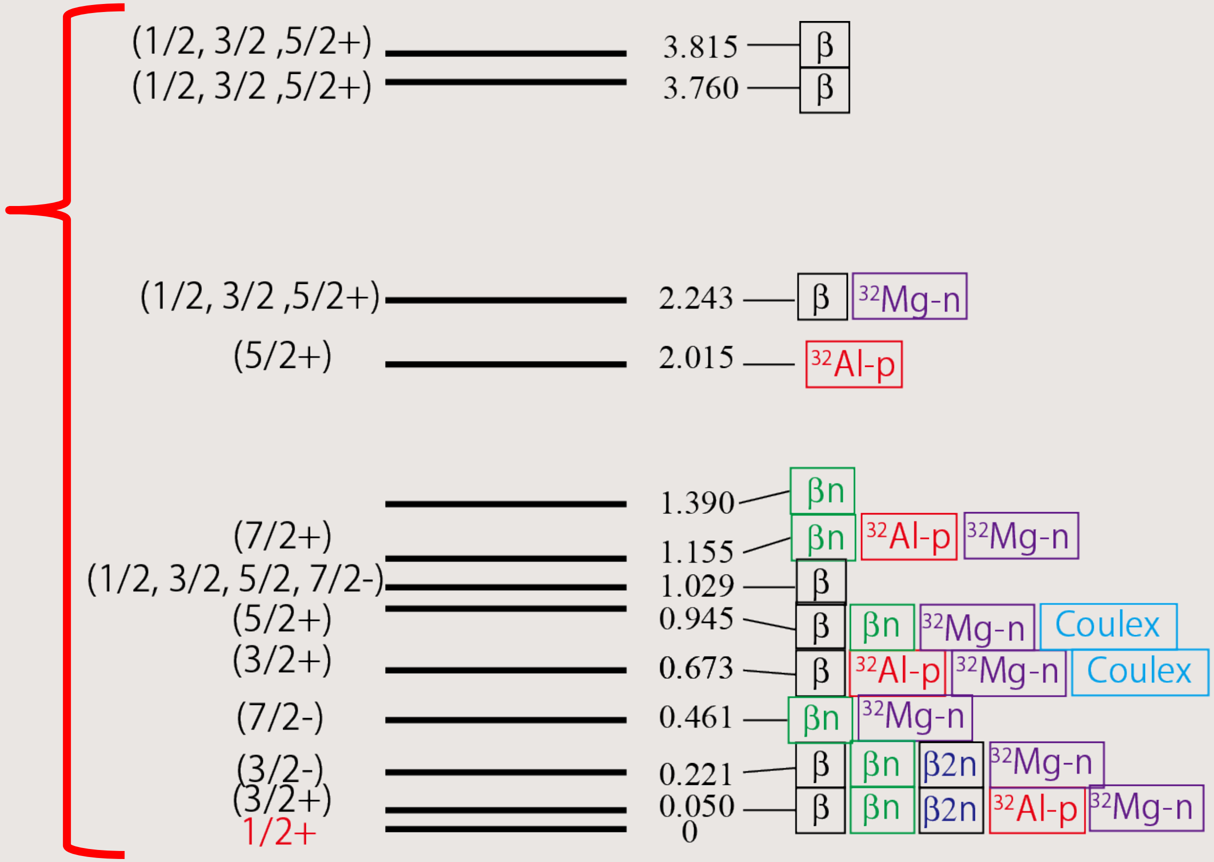
H. Nishibata et al.,
Phys. Lett. B 767, 81 (2017)

Hiroki Nishibata ARIS2017

Adopted levels in ^{31}Mg by Nucl. Data Sheets

Most of the spins and parities are unassigned, except for the 1/2+ ground state.

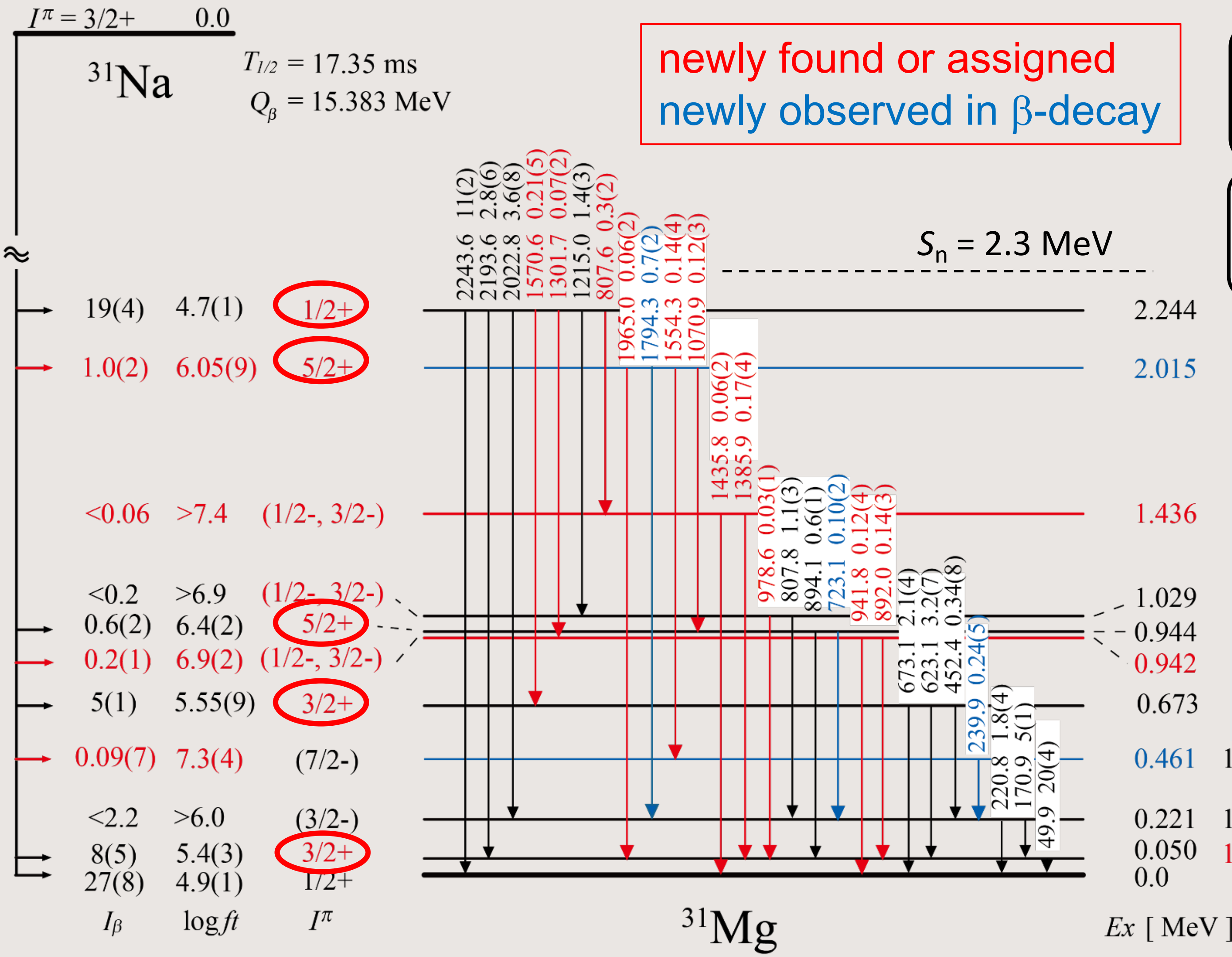
Difficult to discuss structures of ^{31}Mg



Spin-polarized ^{31}Na used to unambiguously assign the spins and parities of the levels in ^{31}Mg populated through allowed GT transition.

C. Quellet et al.,
Nucl. Data Sheets 144, 209 (2013)

Decay scheme of $^{31}Na \rightarrow {}^{31}Mg$



spin polarization via collinear laser optical pumping

P ~32%

^{31}Na+ ion beam intensity:

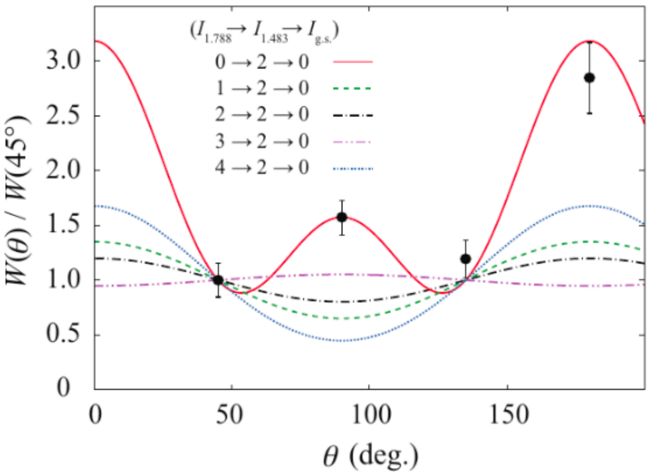
~ 800 pps (extracted), 28keV

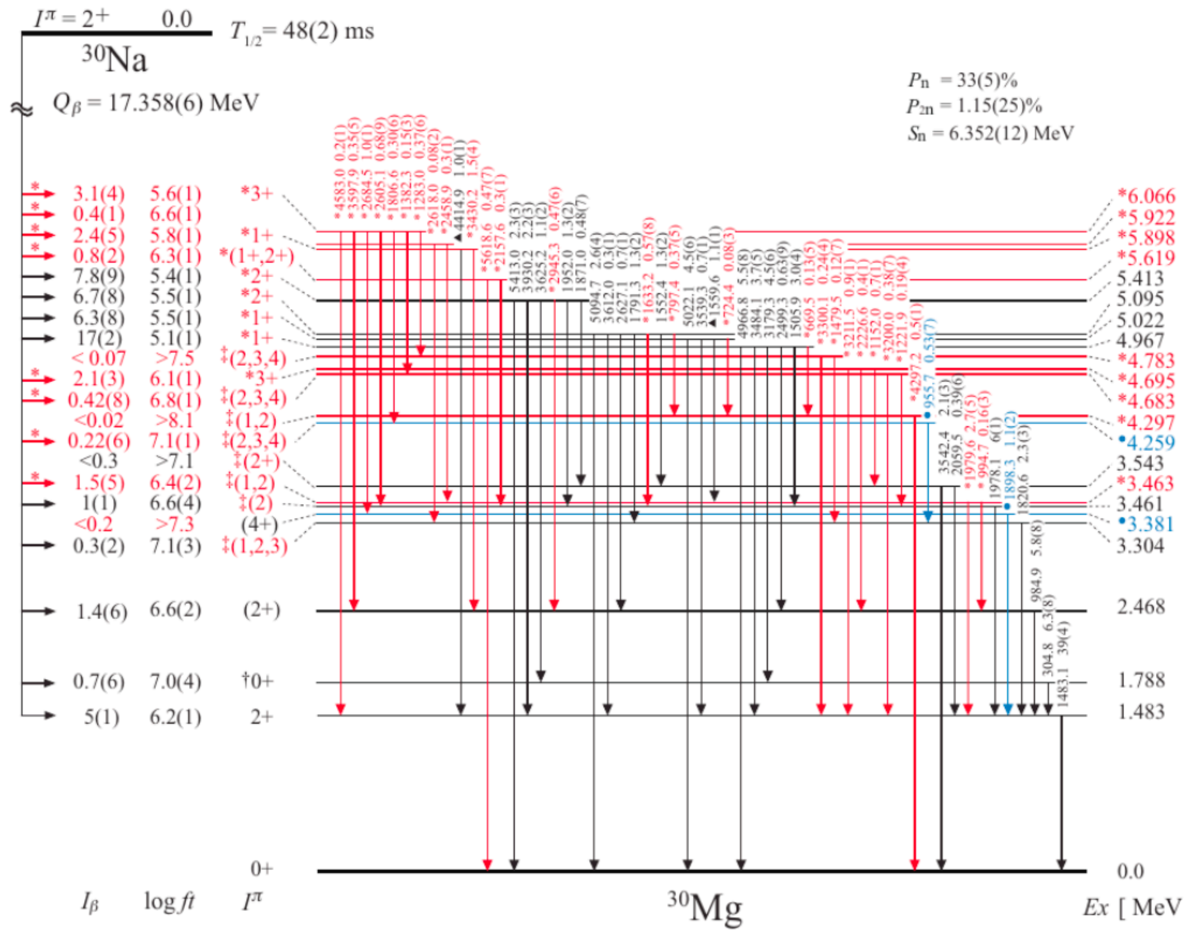
~ 200 pps (after polarizer)

- All spins of the positive-parity levels are assigned.
- From the detailed β and γ transition probabilities, spins of negative parity-levels proposed.

H. Nishibata et al., Phys. Lett. B 767, 81 (2017)

Revised β Decay Scheme
30Na → 30Mg





Thank you!

Questions?