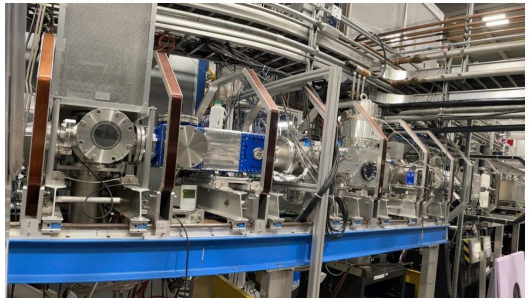
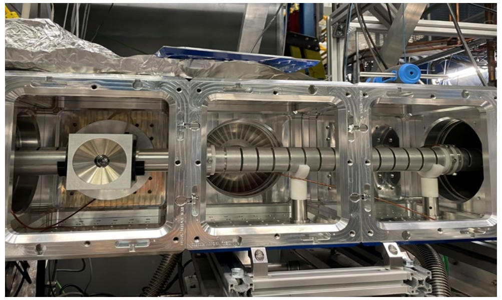
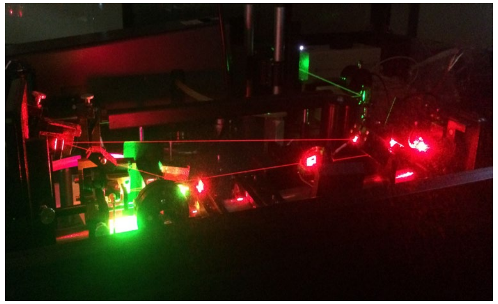
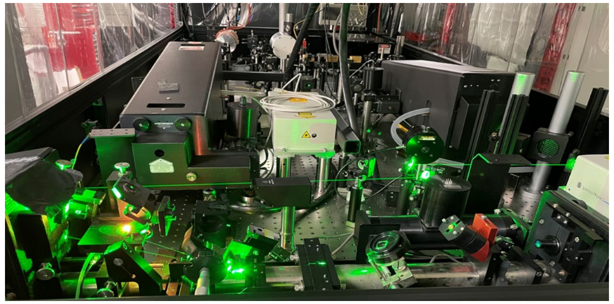
TRIUMF

nuclear spin polarization & collinear laser spectroscopy program at TRIUMF

Ruohong Li

on be half of Targets & Ion Sources – Laser Applications group

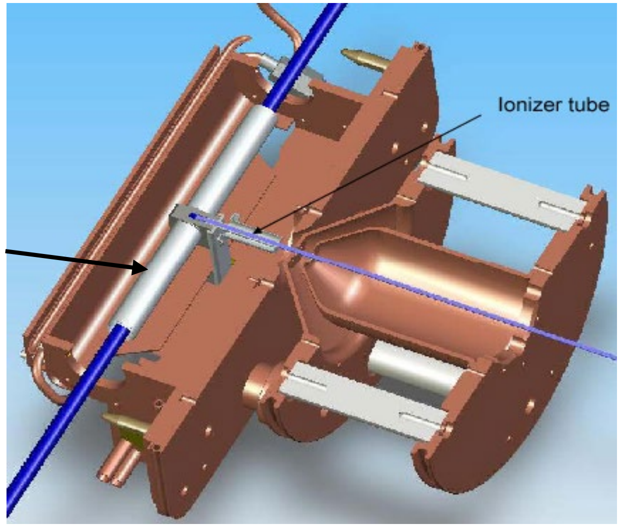
Discovery, accelerated

- **TRIUMF** founded 1968 by SFU, UBC and U Victoria (**TRI**-**U**niversity **M**eson **F**acility)。
- TRIUMF has world's largest cyclotron (**520** MeV, **18-meter** diameter).
- Has **20** Canadian member universities and works with **50** foreign institutions in **30** different countries.
- staffed by **350** scientists, engineers, technicians, and **150** postdoc's, graduate- and co-op- students.

TRIUMF-ISAC （Isotope Separator and Accelerator）

Use radioactive isotopes to study nuclear physics, astrophysics, material science and life science

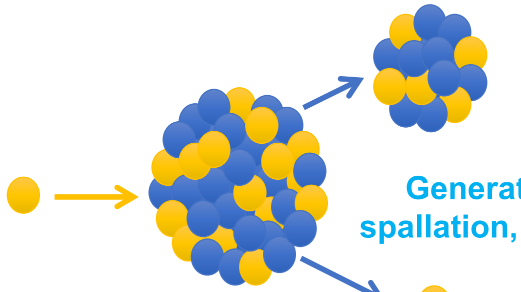
Target



radioactive isotope beam

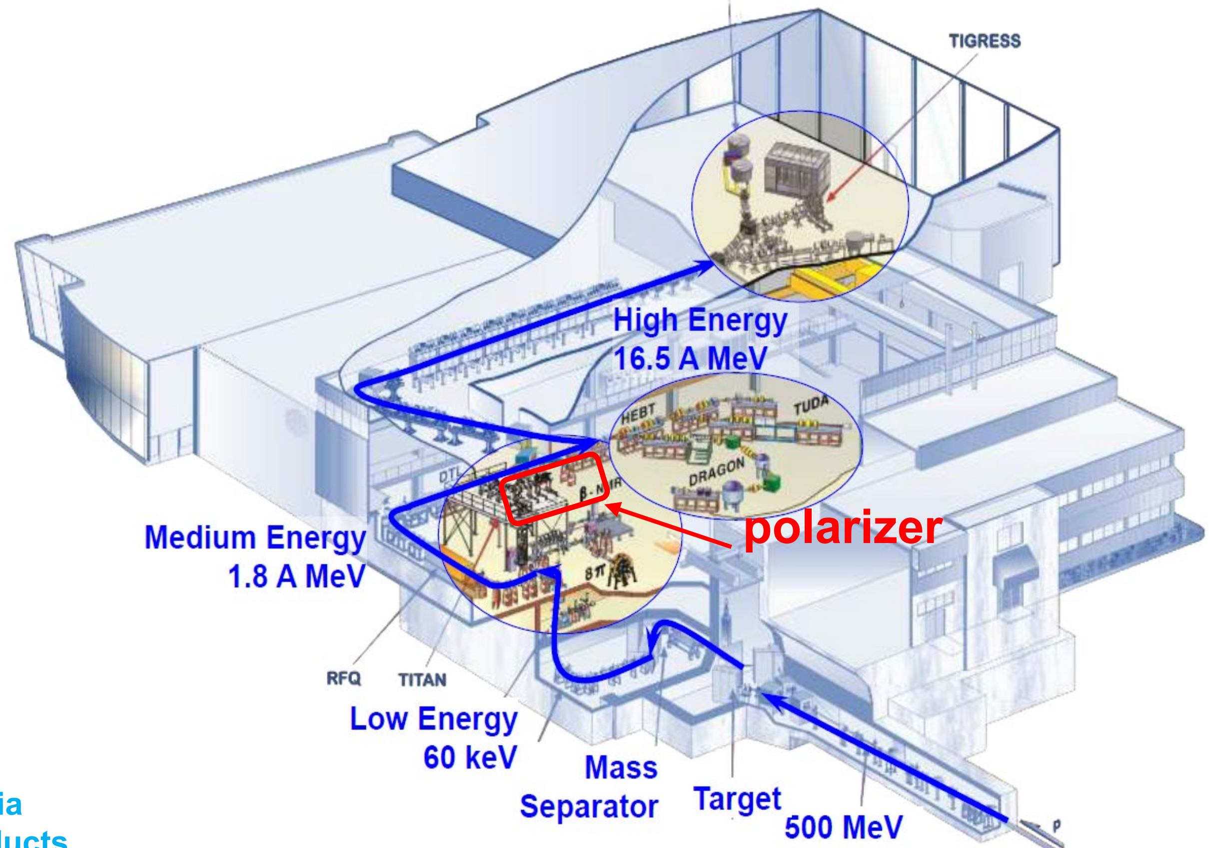
500 MeV p+

p^+



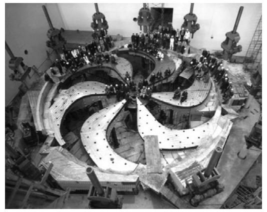
Generation of radioactive isotopes via spallation, fragmentation & fission products

Target Nucleus (U, Ta etc.)



cyclotron

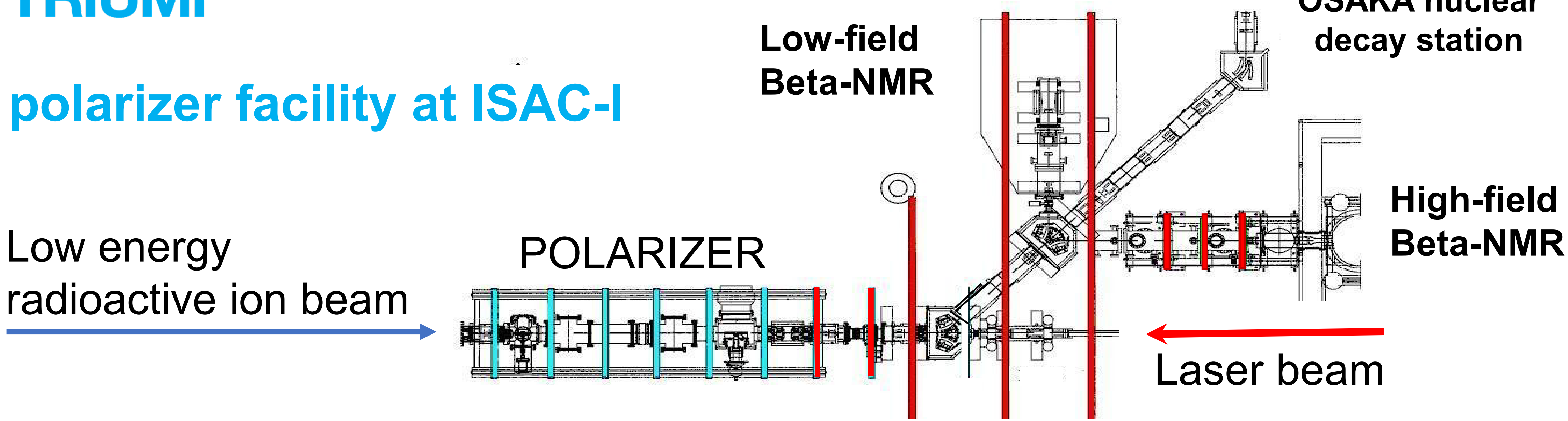
p^+ @ 480 MeV and up to 100μA to ISAC

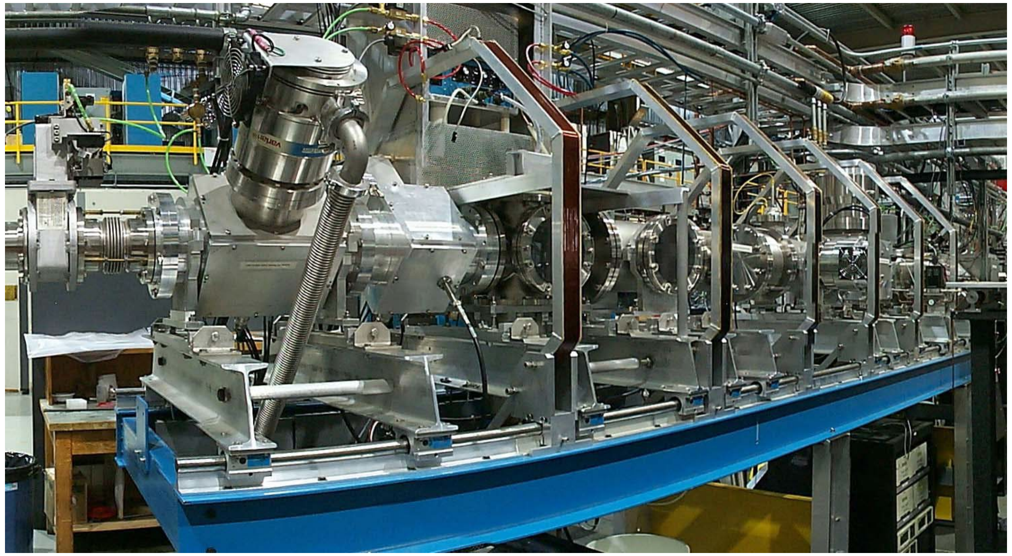


Discovery, accelerated

TRIUMF

polarizer facility at ISAC-I





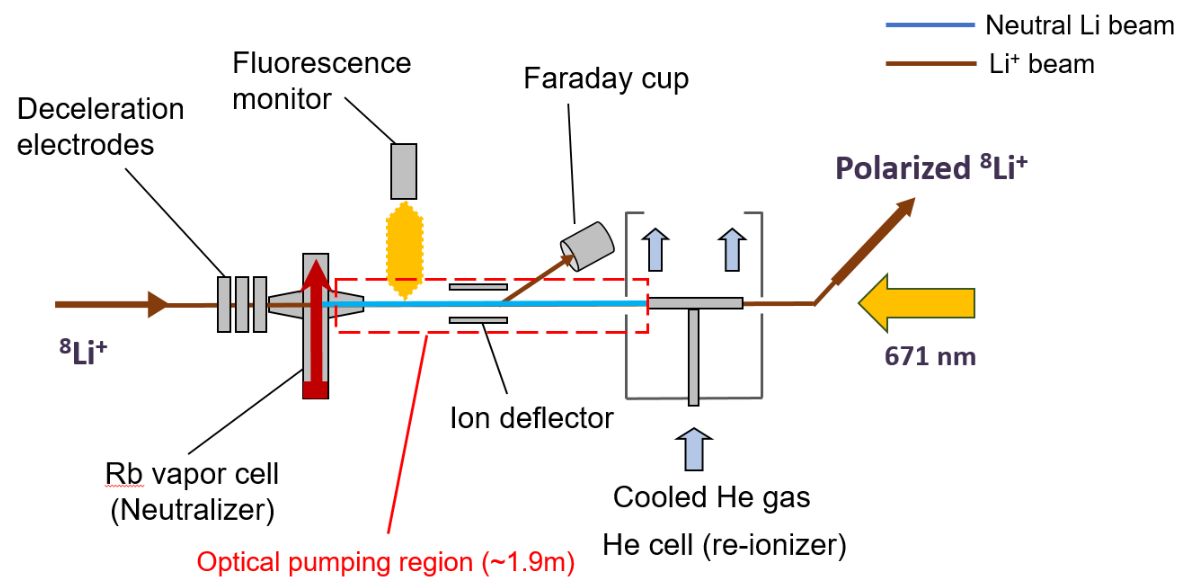
functions: provide **hyperpolarized** (polarization up to 90%) radioactive nuclei **~800 hours/year** for scientific research: beta-detected nuclear magnetic resonance (β-NMR) for material-, life-science, nuclear physics, and fundamental symmetries.

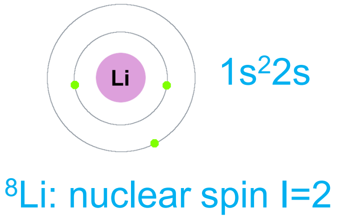
method: collinear **optical pumping** using lasers

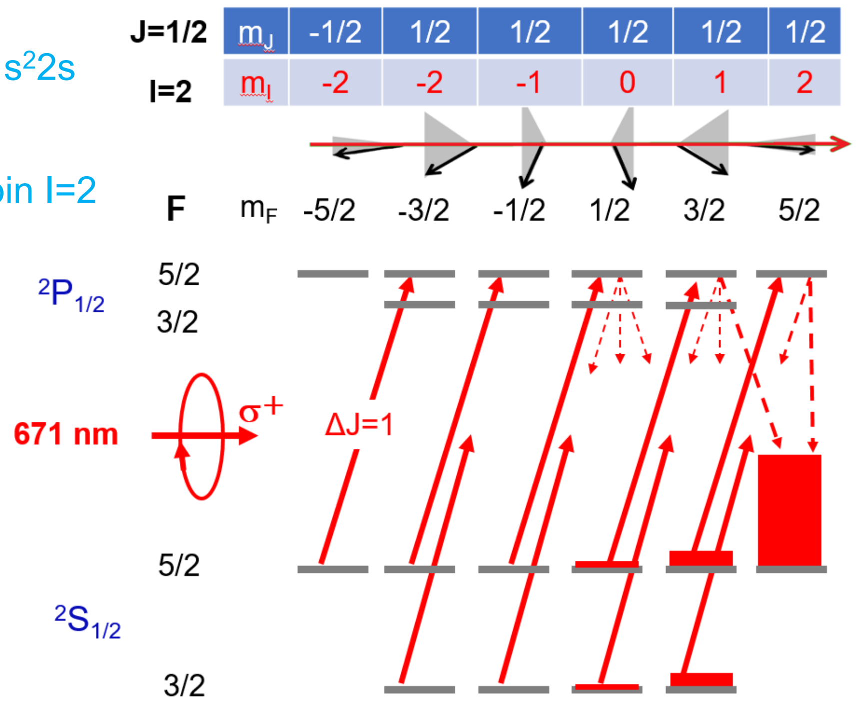
nuclear-polarized beams:

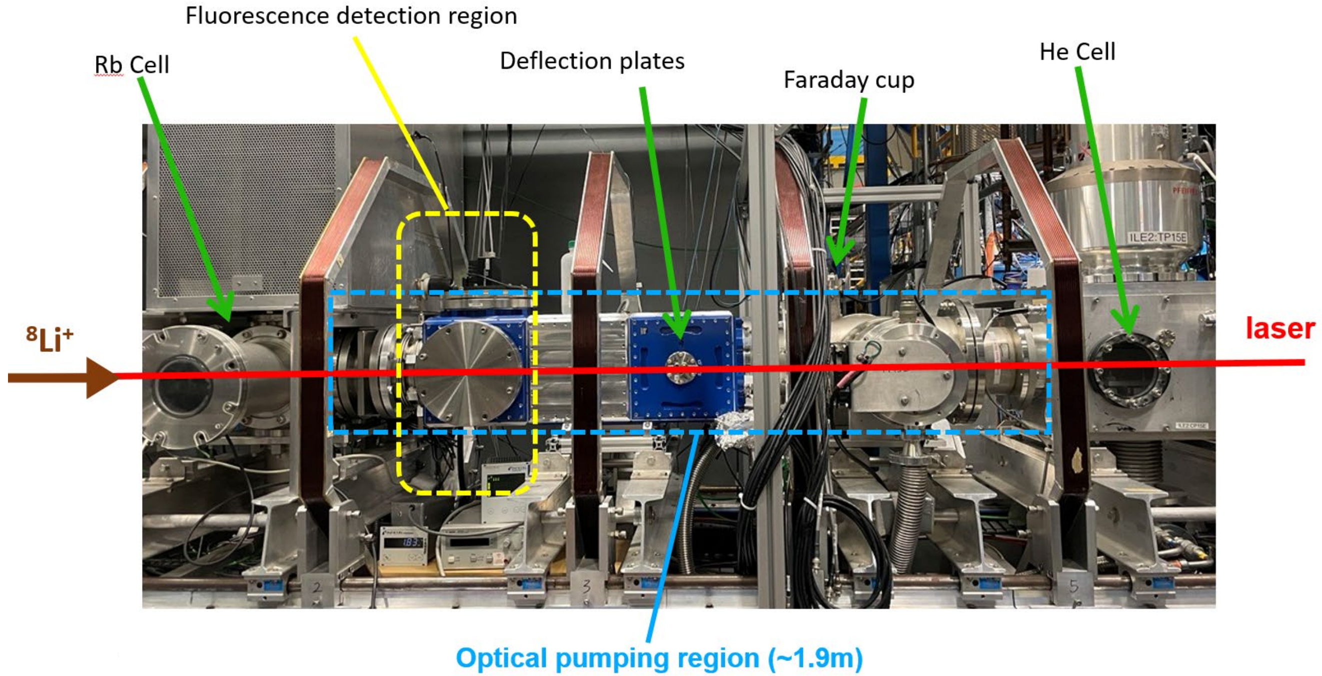
- ^{8}Li, ^{31}Mg(routine delivery), ^{33}Mg (new 2023)
- $^{230, 232}$Ac, ^{58,74}Cu, ^{32}Na etc. (in development)

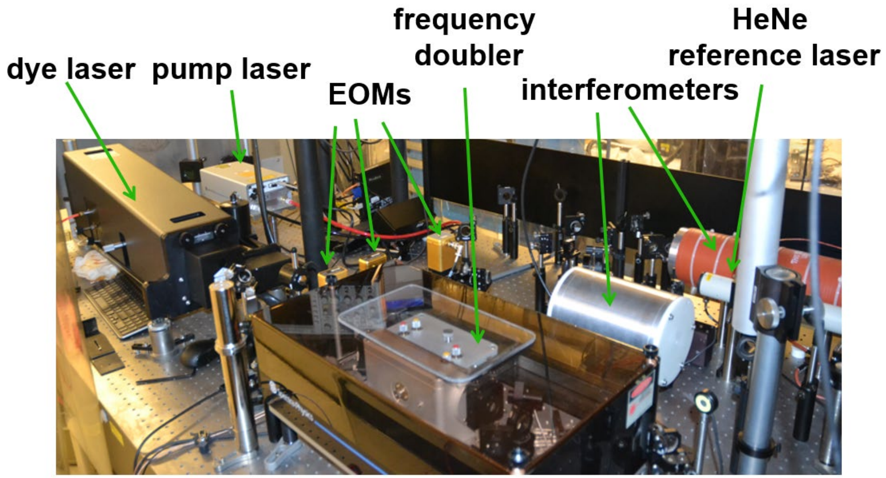
polarized ^{8}Li beam through optical pumping









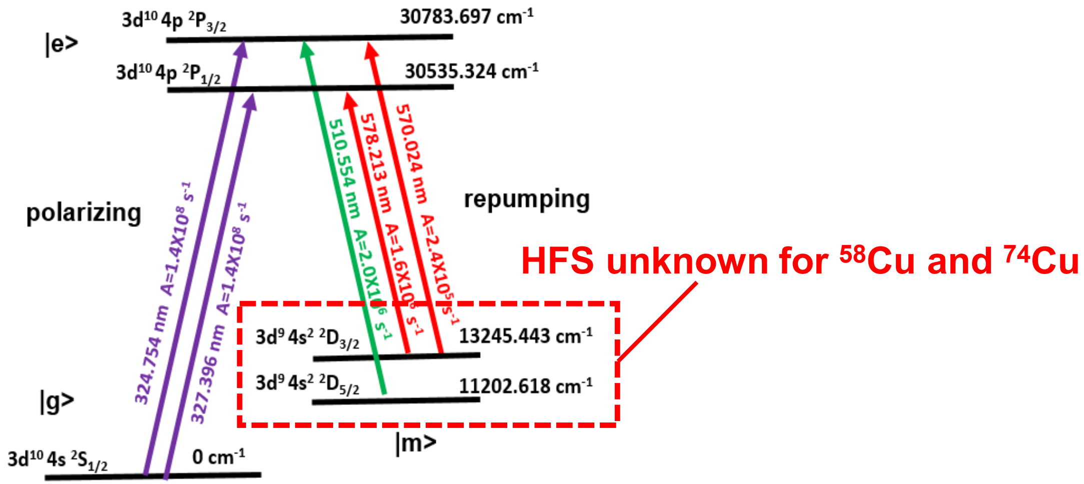


Discovery, accelerated

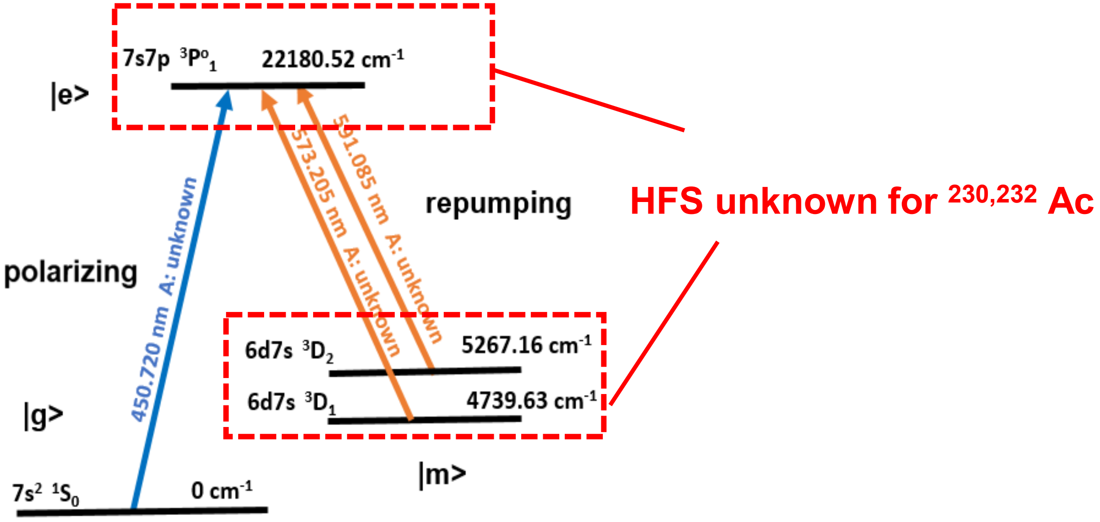
Challenges to polarize exotic isotopes

- different isotopes have different isotope shift (IS) and hyperfine structures (HFS). To manipulate the electron population within these structures, dedicated laser system need to be purchased/developed.

Cu — Alzheimer's disease

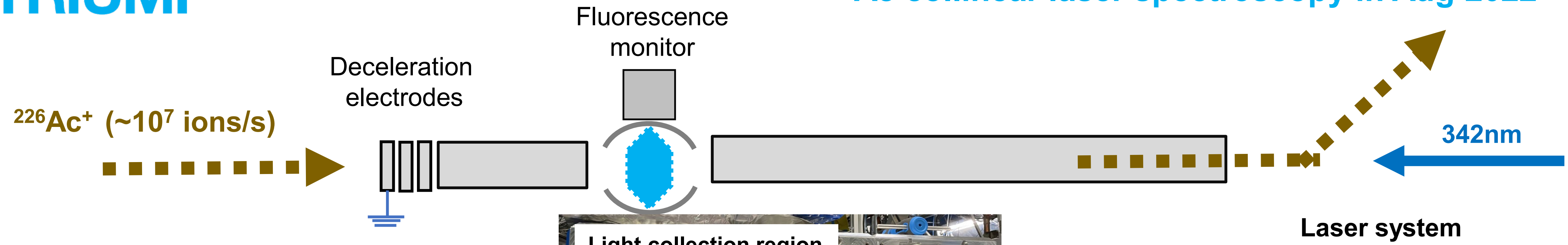


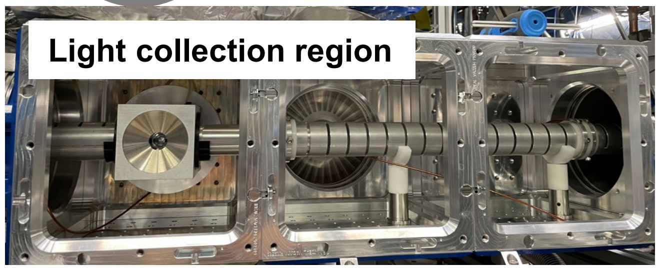
^{225}Ac highly promising for targeted alpha cancer therapy



- difficult wavelength regions: blue or UV which needs frequency doubling
- multiple lasers & modulators needed for pumping and re-pumping the electronic population
- for some isotopes, such as ^{58}Cu, ^{74}Cu, and $^{230, 232}$Ac, hyperfine structures are unknown.
  →collinear spectroscopy to be done before attempting laser polarization.

Ac collinear laser spectroscopy in Aug 2022

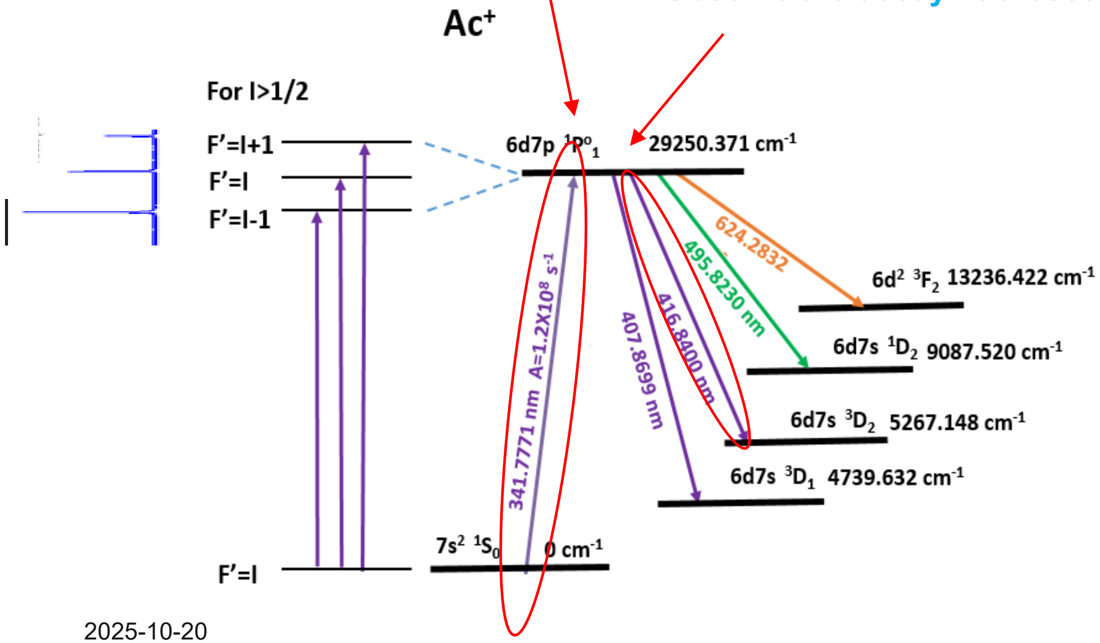


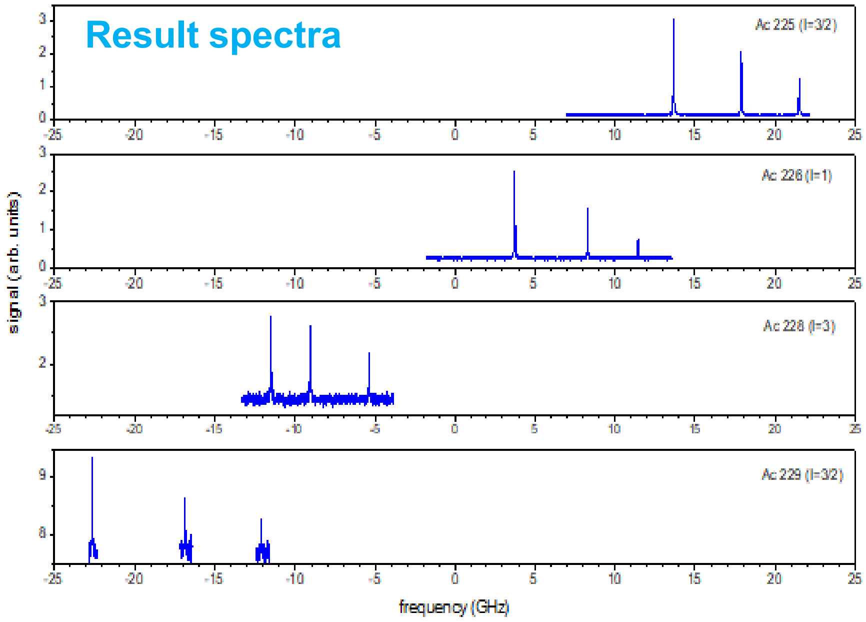


Collaborated with M. Stachura group

Excite this transition using the laser

Observe the decay fluorescence of this transition





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For ^{230}Ac and ^{232}Ac, we could not get the spectra due to the low production rate <10^4/s and limited time

PHYSICAL REVIEW C **111**, 054320 (2025)

Collinear laser spectroscopy on neutron-rich actinium isotopes

Ruohong Li,[1,2,3,*] Andrea Teigelhöfer,[1] Jiguang Li,[4,†] Jacek Bieroń,[5] András Gácsbaranyi,[1,‡] Jake Johnson,[6] Per Jönsson,[7] Victoria Karner,[1] Mingxuan Ma,[4] Martin Radulov,[1] Mathias Roman,[1] Monika Stachura,[1] and Jens Lassen[1,8,9]

High-resolution collinear laser spectroscopy of neutron-rich actinium has been performed at TRIUMF's isotope separator and accelerator facility ISAC. By probing the $7s^2\ ^1S_0 \rightarrow 6d7p\ ^1P_1$ ionic transition, the hyperfine structures and optical isotope shifts in ^{225,226,228,229}Ac$^+$ have been measured. This allows precise determinations of the changes in mean-square charge radii, magnetic dipole moments, and electric quadrupole moments of these actinium isotopes. The improved precision of charge radii and magnetic moments clears the ambiguity in the odd-even staggering from previous studies. The electric quadrupole moments of ^{225,226,228,229}Ac are determined for the first time.

High-resolution spectra of $^{225,\,226,\,228,\,229}$Ac

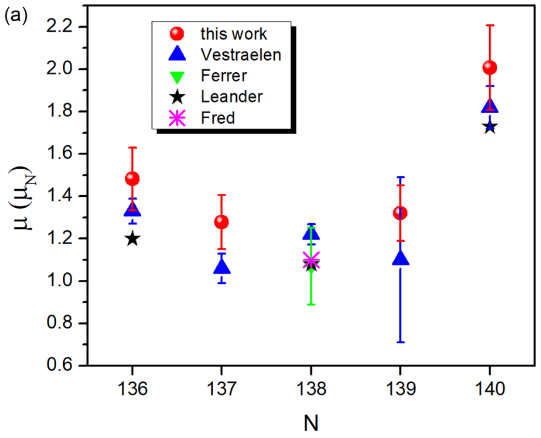
linewidth: ~40MHz
resolved hyperfine structure

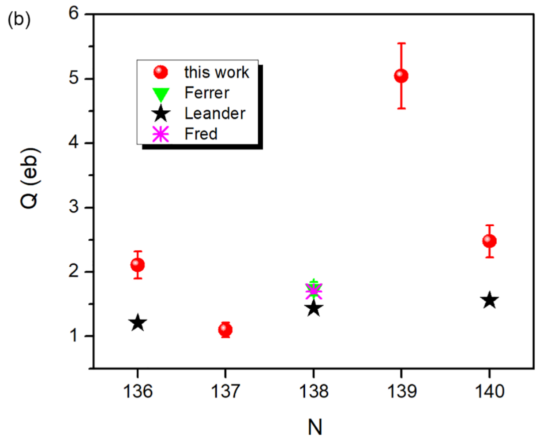
extracted hyperfine constants and isotope shift

nuclear properties can be further extracted:

- **change of charge radii $\delta\langle r^2\rangle$**
- **nuclear magnetic dipole moment μ**
- **nuclear electric quardrupole moment Q**

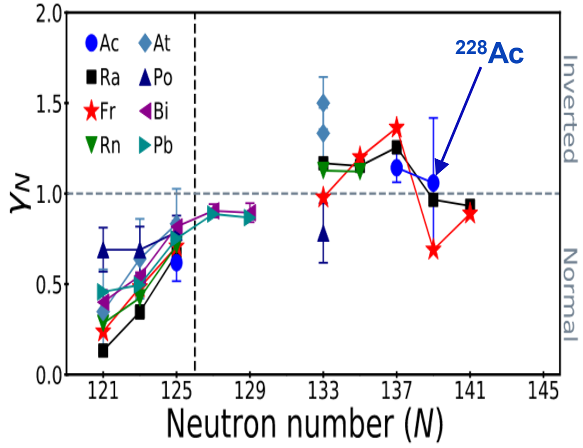
measured μ and Q (first time) of $^{225,\,226,\,228,\,229}$Ac

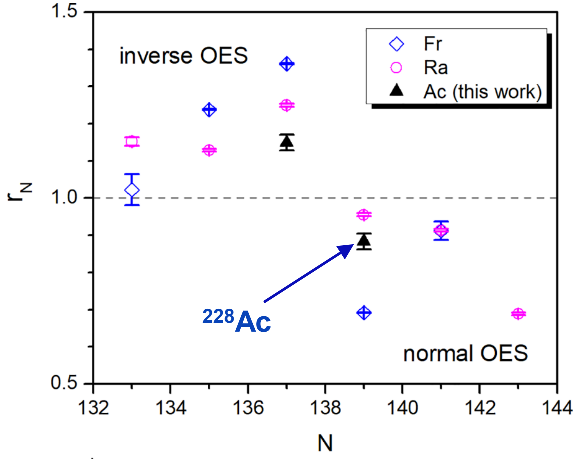




Determine the clear boundary of inverse OES

Previous work





E. Verstraelen et al. Phys. Rev. C 100, 044321 (2019)

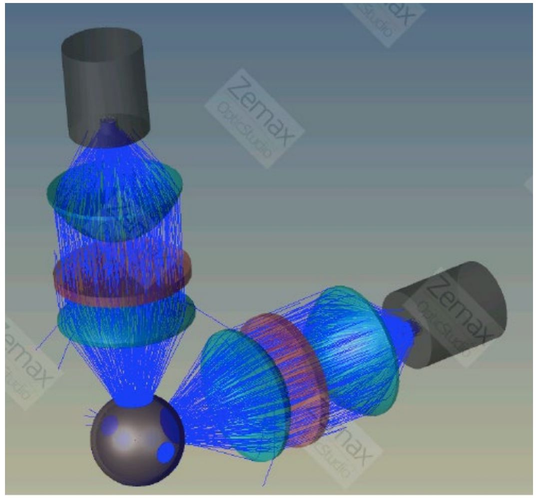
TRIUMF

How to improve our detection efficiency?

To polarize exotic isotopes with low production rates: e.g. ^{230}Ac (<10^4/s), ^{32}Na(~100/s)), CLS is required to determine relevant HFS and IS

Improve the fluorescence detection system

Spherical mirror system designed by OSAKA/TRIUMF
(used for Ac$^+$ CLS experiment online in 2022)



collection eff:
11% one axis
22% two axes
combined

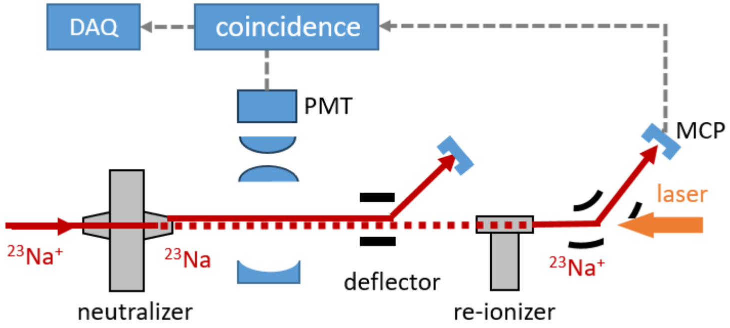
Improve on photomultiplier tube: bigger PMT detection area
higher quantum efficiency
lower dark counts

^{23}Na stable beam test in 2017 and 2023:
total detection efficiency is 5-15×10^{-5}

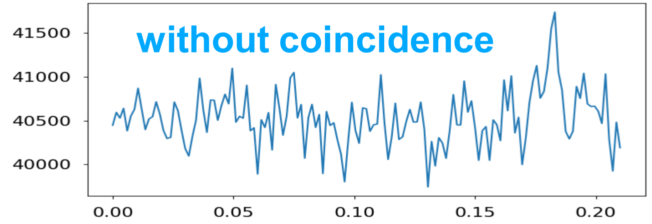
Developing is continuing

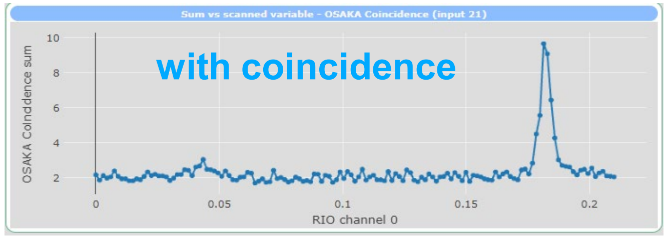
Photon-ion coincidence method

^{23}Na stable beam test in 2023 with OSAKA group



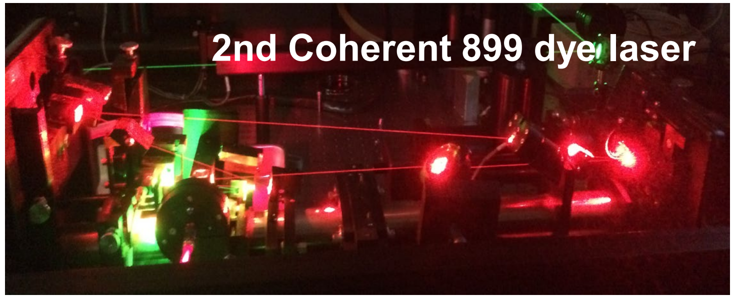
^{23}Na ~2×10^4/s

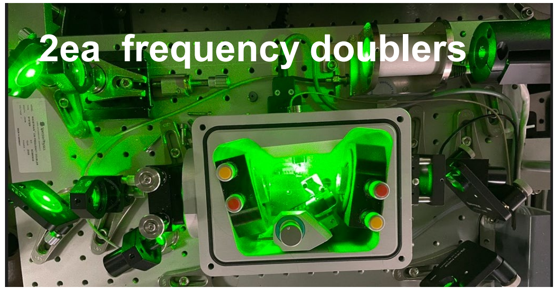




TRIUMF

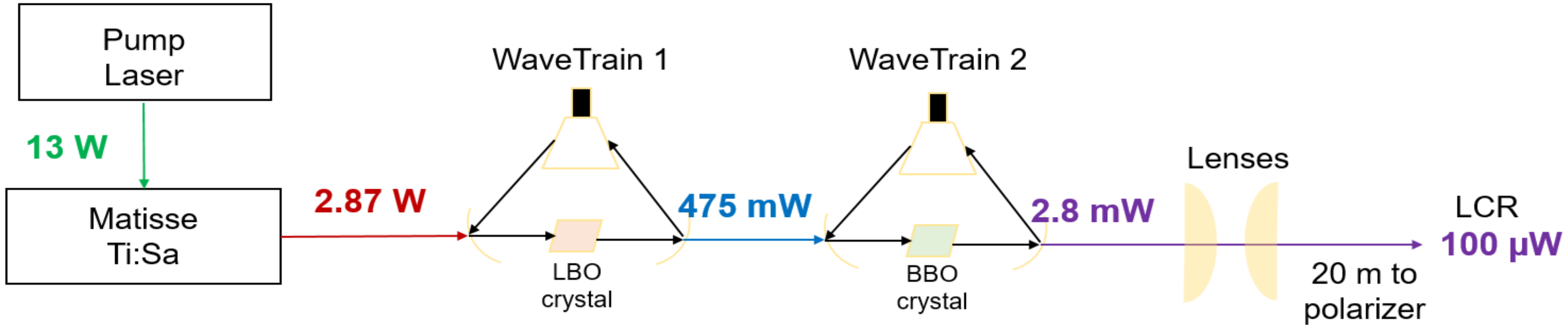
upgraded laser systems for polarized beams & collinear laser spectroscopy



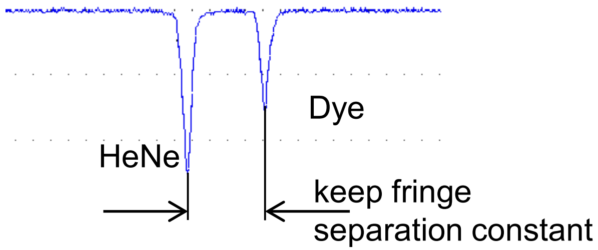


- 2nd coherent 899 dye lasers + frequency doubler + fringe offset lock
- 1ea Matisse CS Ti:Sa laser + 1ea frequency doubler + 1ea fringe offset lock

produced cw 216 nm laser light for Cu, At CLS, Katarina Preocanin, MSc SFU (2025)



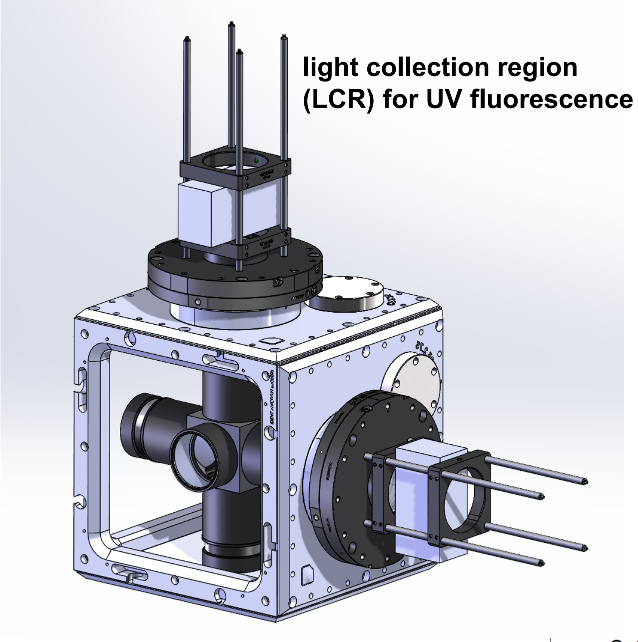
fringe offset lock

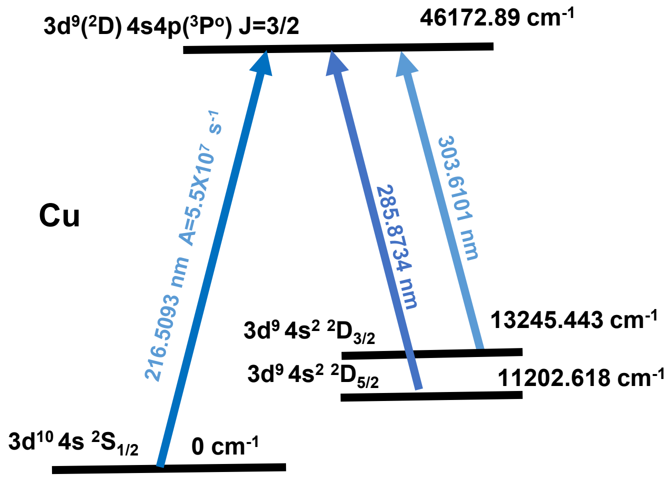


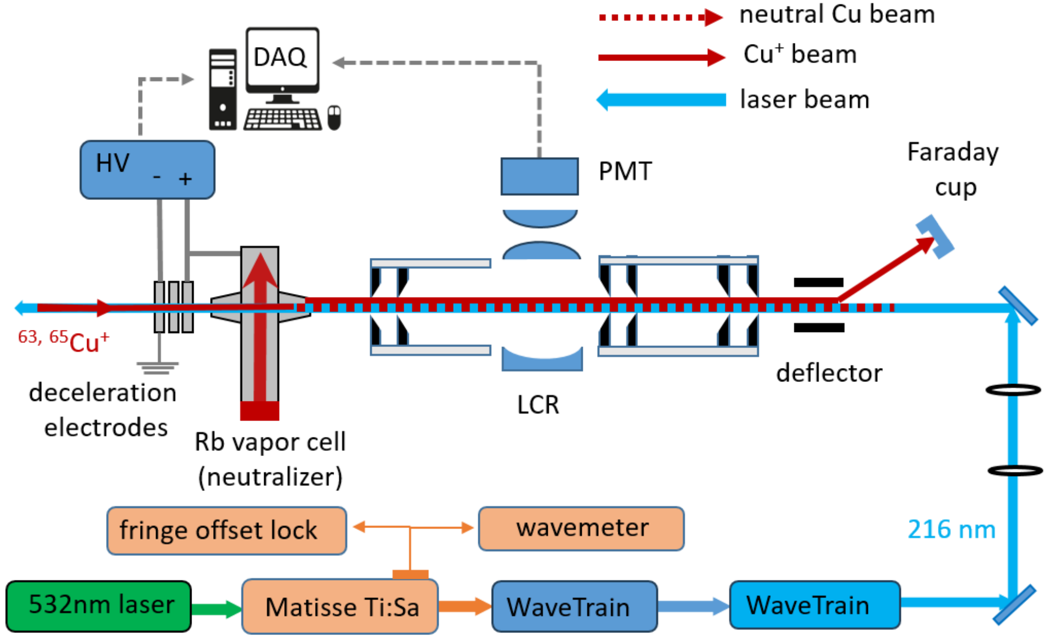
- ❑ 300 MHz free-spectral-range scanning interferometer temperature stabilized to 0.1 °C and hermetically sealed.
- ❑ major cause of laser drift is air pressure variation.
- ❑ long-term dye laser frequency stability is +/- 5 MHz, determined by the HeNe reference laser stability and scan non-linearities.

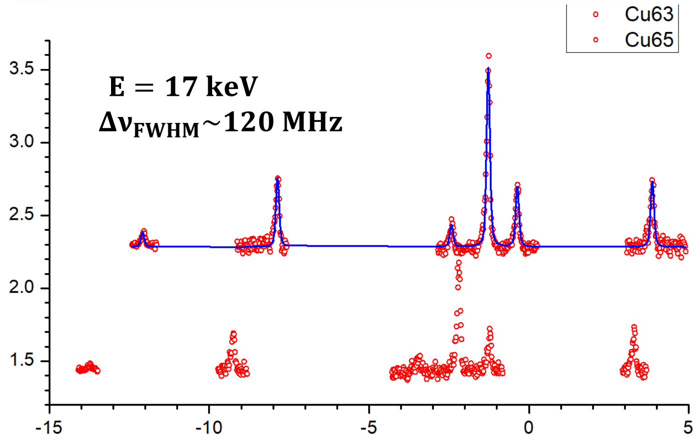
Cu CLS experiment with OLIS beam (2025)

UV optical detection system for CLS
transition wavelength = 216 nm
OLIS stable beam → 1.4×10^{8} atoms/s Cu









2025-10-20

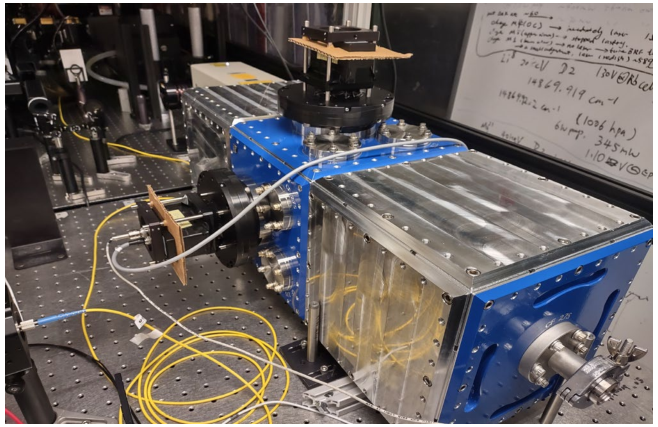
Cu63,65 $\quad {}^2S_{1/2}$ -> J=3/2 (216.5 nm)

	I	A($^2S_{1/2}$) MHz	A(J=3/2) MHz	B(J=3/2) MHz
^{63}Cu	3/2	5866.92(1)	2168(13)	?(?)
^{65}Cu	3/2	6284.41(3.5)		?(?)

new data for A, B hyperfine constants for 216.5nm Cu transition

UV LCR works with detection eff. of 1.2 and 1.7E-6 per neutral Cu atom for horizontal and vertical arms, respectively, by assuming neutralized population are all at the ground state.

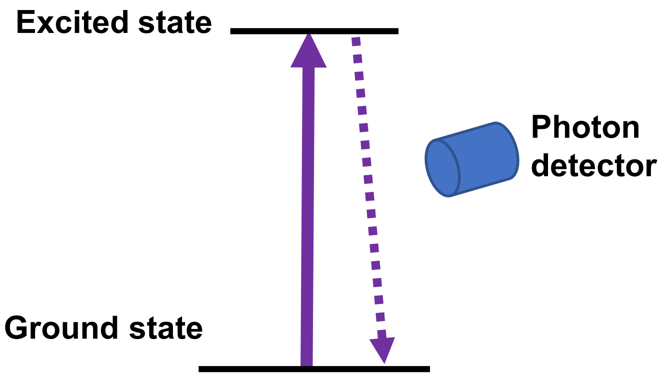
further improvement ongoing on the LCR (offline test)



collinear resonant ionization spectroscopy at TRIUMF

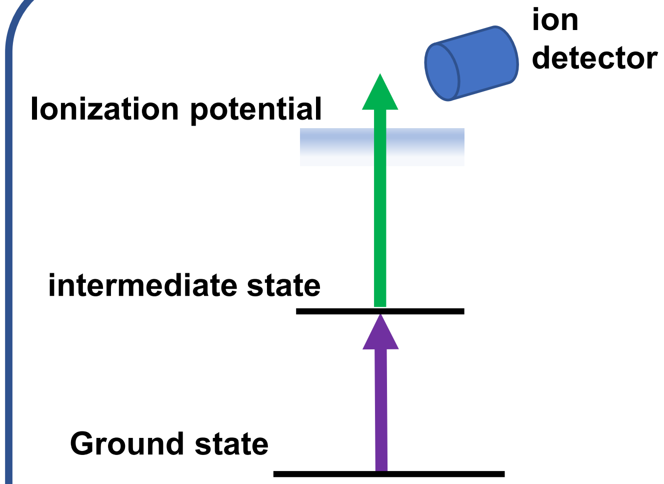
Resonance ionization spectroscopy in collinear geometry RISIKO as developed at Mainz U around 1990 and implemented at CERN-ISOLDE with CRIS around 2010, allows collinear laser spectroscopy with beam intensity as low as 20/s (^{78}Cu, R. P. de Groote et al., Phys. Rev. C 96, 041302 (2017).)

Fluorescence method



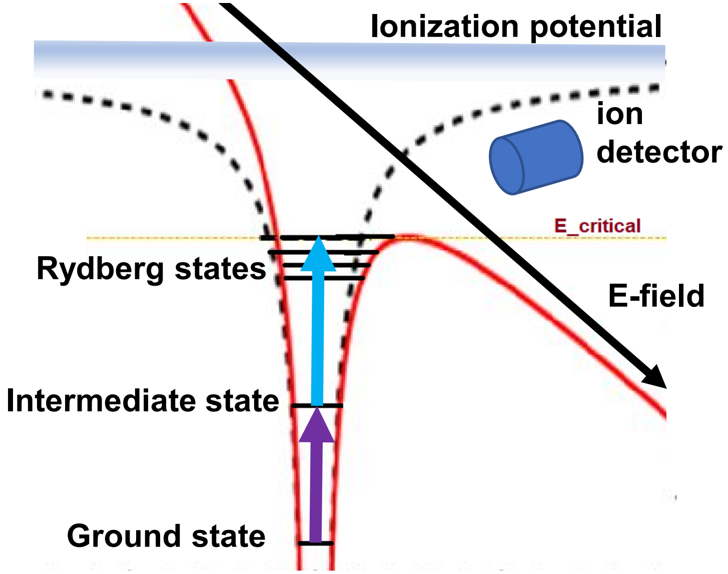
- Difficulty to collect 4π fluorescence
- Photon detection efficiency not high
- Suppress the stray light and dark counts

RISIKO & CRIS



- Efficient charge particle detection(~100%)
- Nonresonant ionization needs high laser power→pulsed laser→bunching beam
- Background ions generated by collision with residual gas(need high vacuum to 10^{-10} mbar)

RISIKO & CRIS with Rydberg-state field ionization

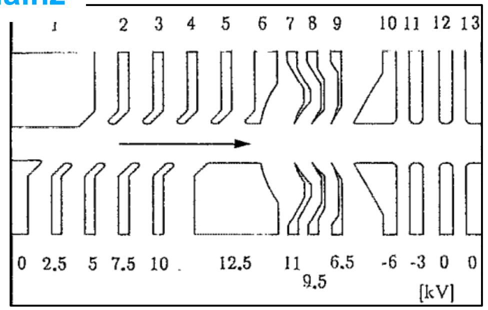


- Efficient charge particle detection(~100%)
- Efficient resonant excitation + field ionization
- Field ionizer- allow mark the energy of the beam which are generated inside→allow the separation of the background ions and signal ions.

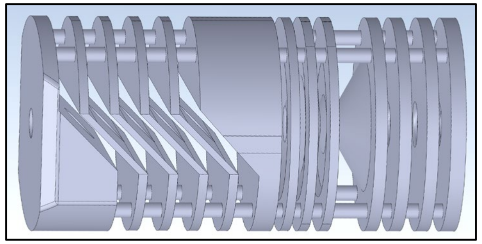
Simulate and built Rydberg-state field ionizer

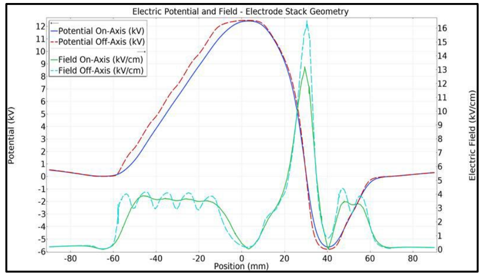
2023 Co-op student project (Aryan Prasad)

Mainz

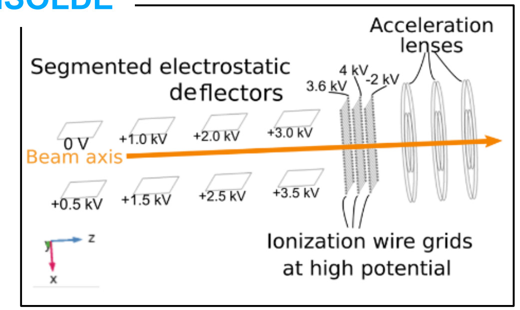


Our simulations:

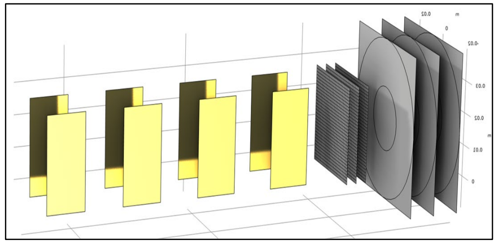


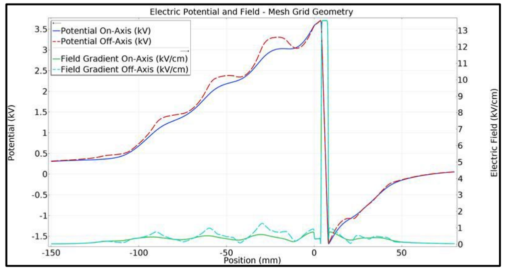


ISOLDE



Our simulations:





Design Goals:

- **Simulate the Mainz and ISOLDE designs using COMSOL**

  Mainz: K. Stratmann et al., Rev. Sci. Instrum. 65, 1847 (1994).

  ISOLDE: A. R. Vernon et al., Sci. Rep. 10, 12306 (2020).

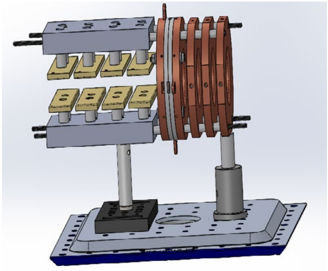
- **Adapt the ISOLDE design into ISAC-polarizer**

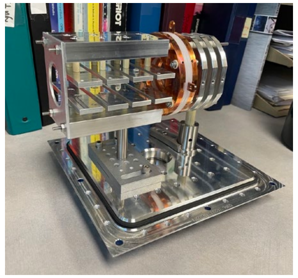
Simulation results:

Both geometries had a **gradual rise in potential** followed by a **steep drop** and a subsequent rise to ground.
The sharp potential drop establishes a **localized region** of **high field** where Rydberg atoms are ionized.

Mainz: gradual field drop allows for Rydberg state identification through energy analysis,
ISOLDE: indiscriminate ionization with less energy spread.

Rydberg-state field ionizer based on ISOLDE has been built

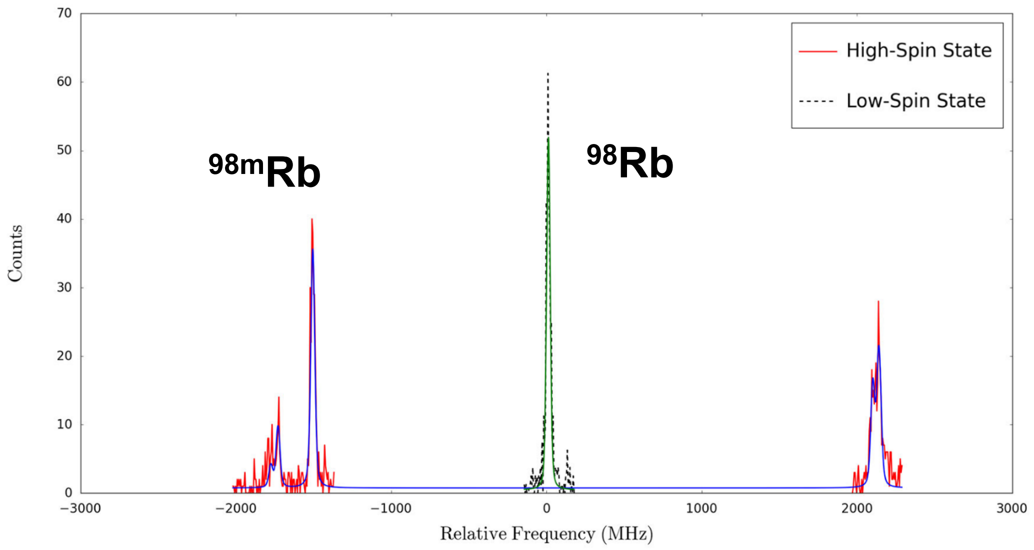




The original RISIKO field–ionizer from Mainz U will be implemented and compared to ISOLDE field-ionizer for high sensitivity collinear laser spectroscopy at TRIUMF.

implementing Rydberg-state field-ionizer will provide isomer-selected beams to OSAKA and GRIFFIN

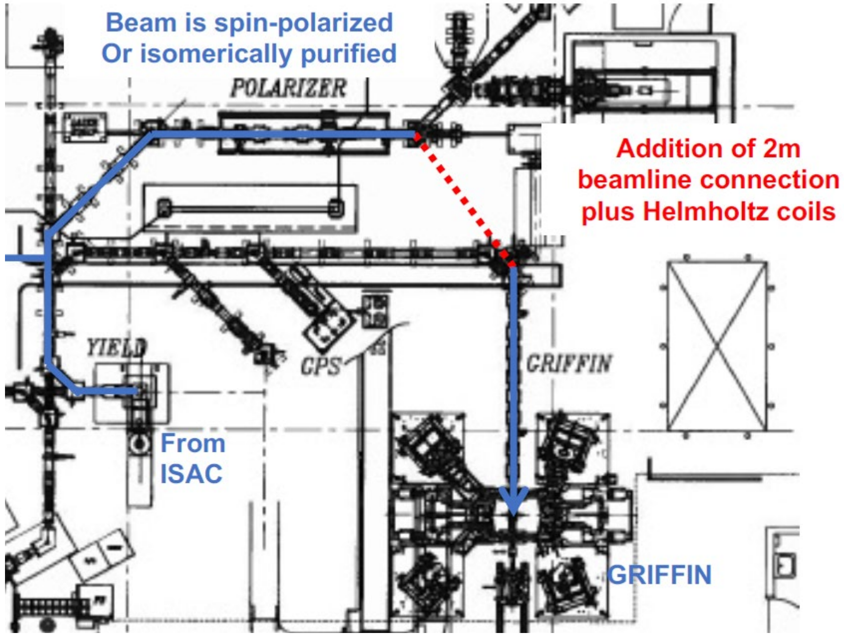
collinear resonant laser ionization allows delivery of isobar-free beams for nuclear spectroscopy



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

S1475 (M. Rajabali, Tennessee Tech Uni.)

cw RIB with Rydberg-state field ionizer avoids beam bunching, while allowing background free beam delivery of isobar free, and possibly polarized beams



beamline extension for polarized beams to GRIFFIN spectrometer (2027)

universal polarizer (future)?

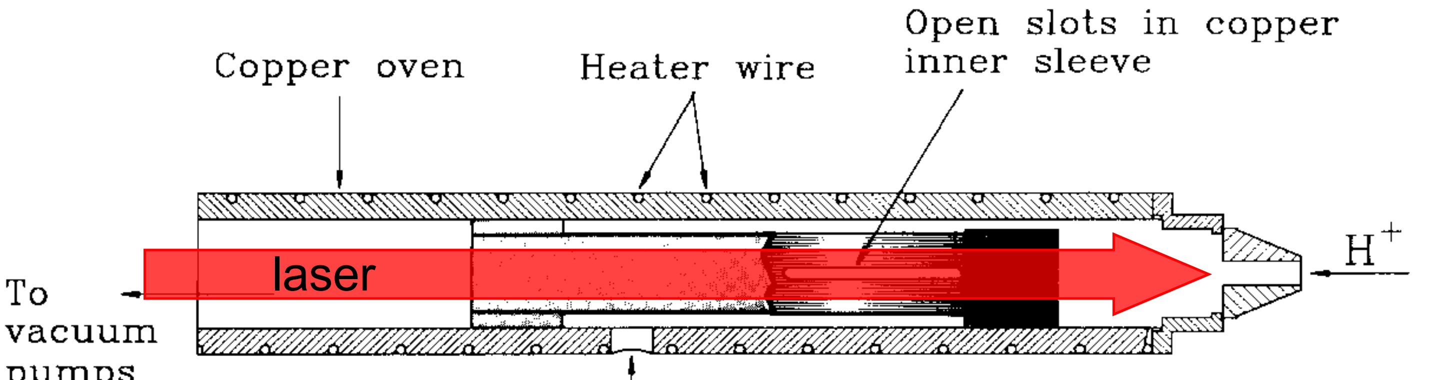
a spin-polarized alkali-vapour mixture as a spin-exchange medium to transfer polarization to ion beams.

alkali-vapor spin-exchange cell:

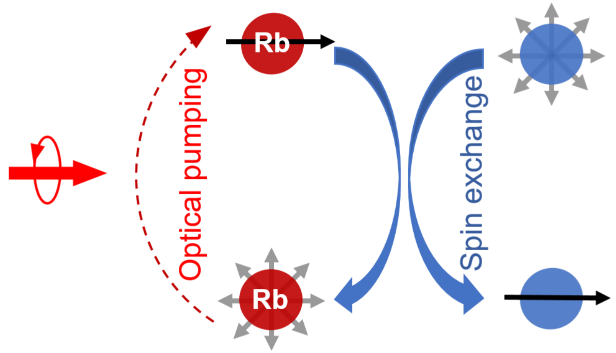
😃 Simply and one laser setup for polarizing one alkali element.

🥺 radiation trapping causes depolarization in dense vapor. Possible solution: mixture of two alkali species

🥺 Depolarization on the cell wall. Possible solution: non-depolarizing wall coating



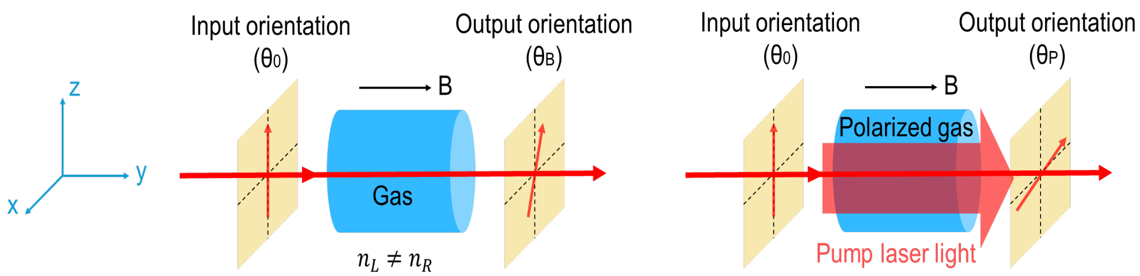
A.N. Zelenskii et al. NIM A 334 (1993) 285-293



Similar configuration as the optically-pumped polarized H^- ion source designed at TRIUMF previously. H^+ passes through optically pumped Rb vapor in a neutralizer cell and picks up polarized electrons by charge exchange to form electron-polarized neutral H atoms.

TRIUMF

Faraday rotation offline test setup



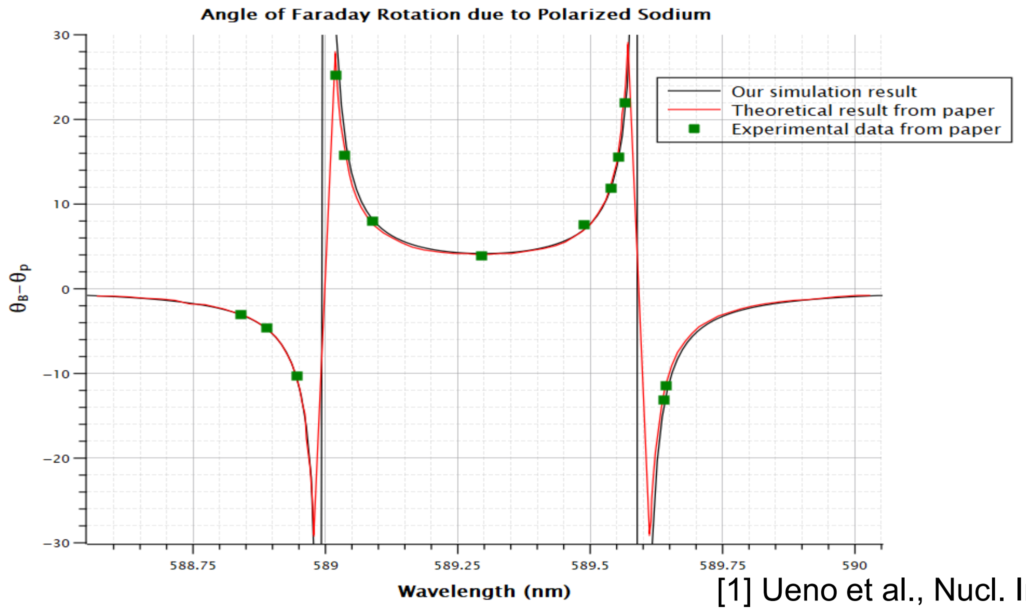
$Nl = \dfrac{\theta_B - \theta_0}{V}$	$P = \dfrac{\theta_P - \theta_B}{\alpha(\theta_B - \theta_0)}$	V – Verdet constant α – alpha constant Both constants depend on magnetic field and the wavelength of the laser.
N – atomic density (temperature dependent) l – length of interaction between gas and laser	P – spin polarization of the gas	

2025 Co-op student project (Simon Liu, Enzo Picinini, Anna Parker, Kenney Lai, Mehar Sahota)

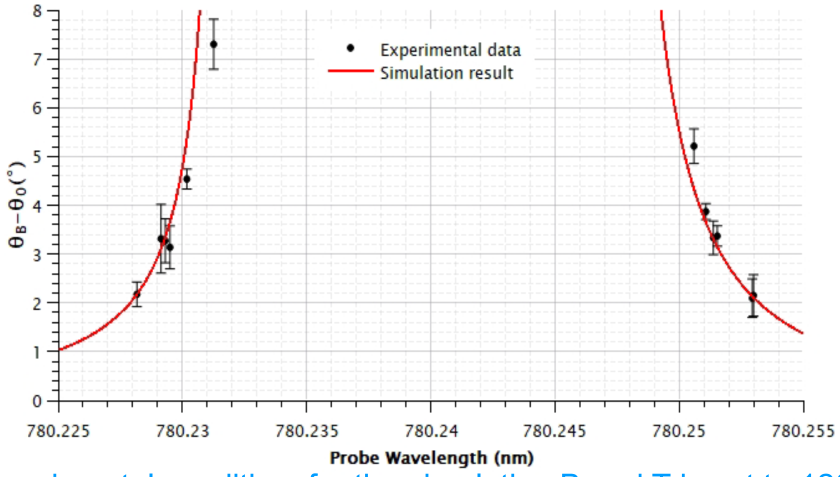
The Verdet and α constants are computed numerically over a range of magnetic fields B and wavelengths λ.

- To describe both weak- and strong-field coupling regimes, the method employs Hamiltonian matrix formalism.
- Starting from the $|LSJM_JM_I\rangle$ basis (which corresponds to the strong-field limit), the full Hamiltonian is constructed, including Zeeman and hyperfine interactions.
- The Hamiltonian is then diagonalized at each magnetic field to obtain the eigenvalues and eigenvectors, from which the transition energies and strengths—and thus the Verdet and α constants—are derived.

test our numerical simulation code by comparing with Ueno et al. [1]

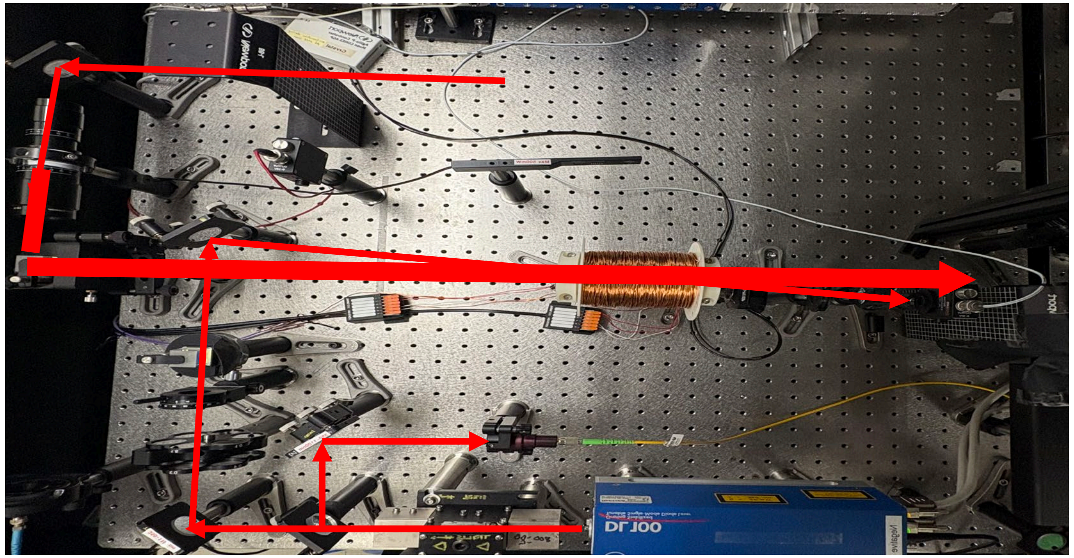


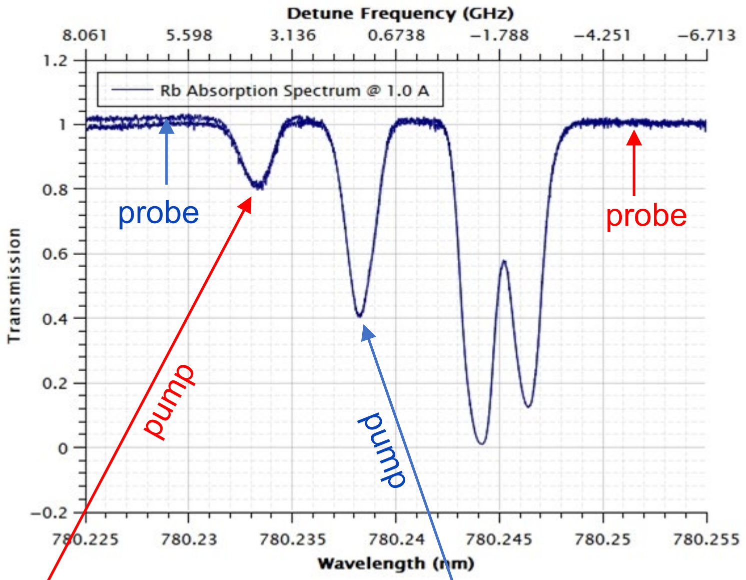
test our numerical simulation code by comparing with our experimental data

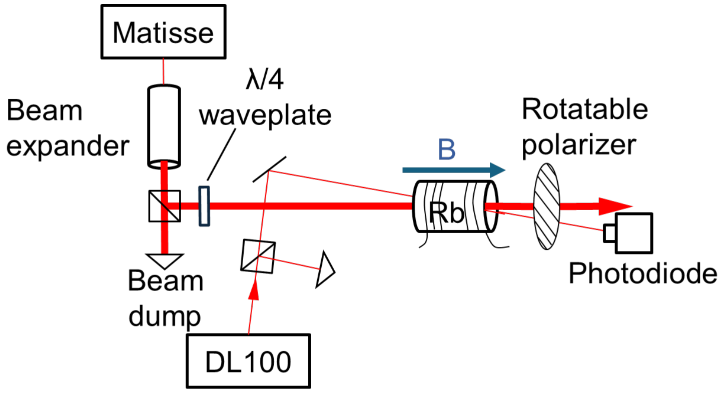


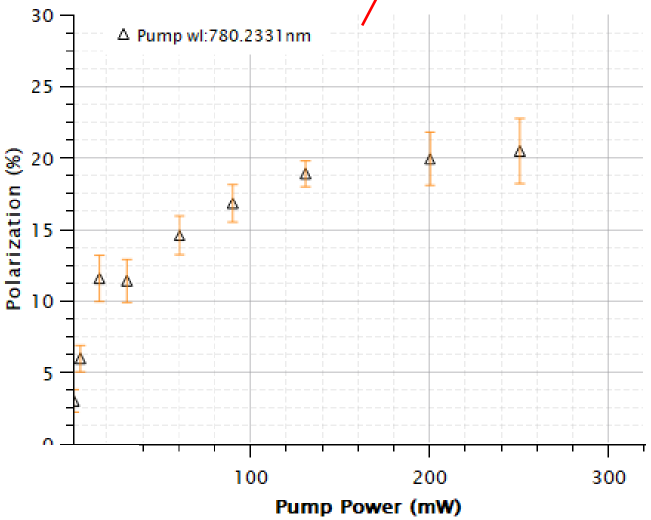
To match our experimental condition, for the simulation B and T is set to 120G, 53˚C.

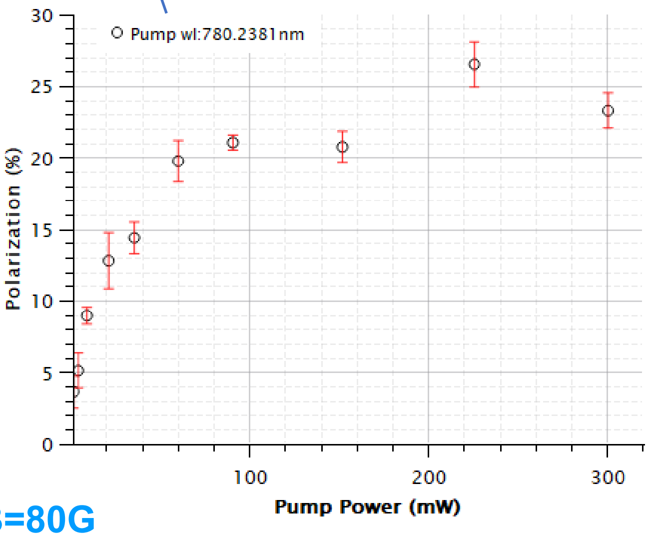
[1] Ueno et al., Nucl. Instrum. Meth. Phys. Res. A 262 (1987) 170











B=80G

- Matisse cw Ti:Sa laser: circularly polarized laser for pumping.
- Toptica diode laser DL100: linearly polarized laser for probing.

Thank you for your attention

Questions?

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We gratefully acknowledge the help & support from TRIUMF, collaborating Universities & NSERC funding

TRIUMF | NSERC CRSNG | UBC | OSAKA UNIVERSITY | SFU SIMON FRASER UNIVERSITY | University of Windsor | University of Manitoba | Saint Mary's University