TRIUMF

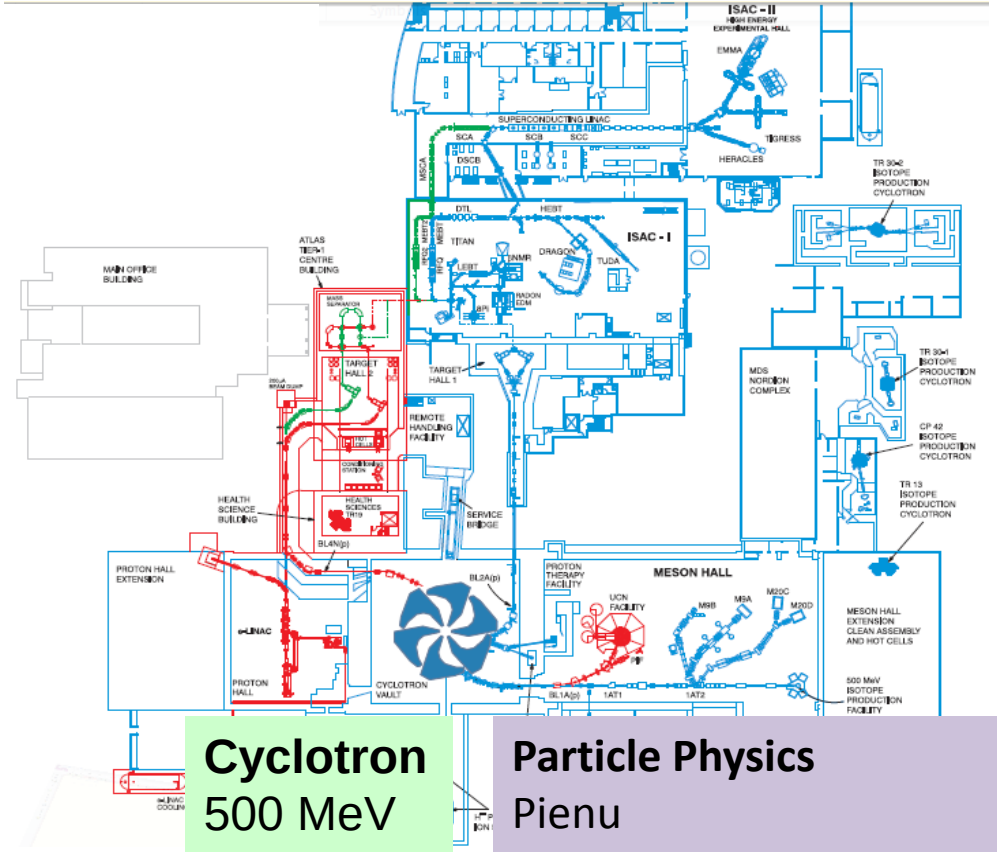
Canada's National Laboratory for
Particle and Nuclear Physics

# The ISAC and ARIEL Facilities at TRIUMF

Jens Dilling
Associate Director
Physical Science Division

December 12th 2016

# TRIUMF's accelerator complex



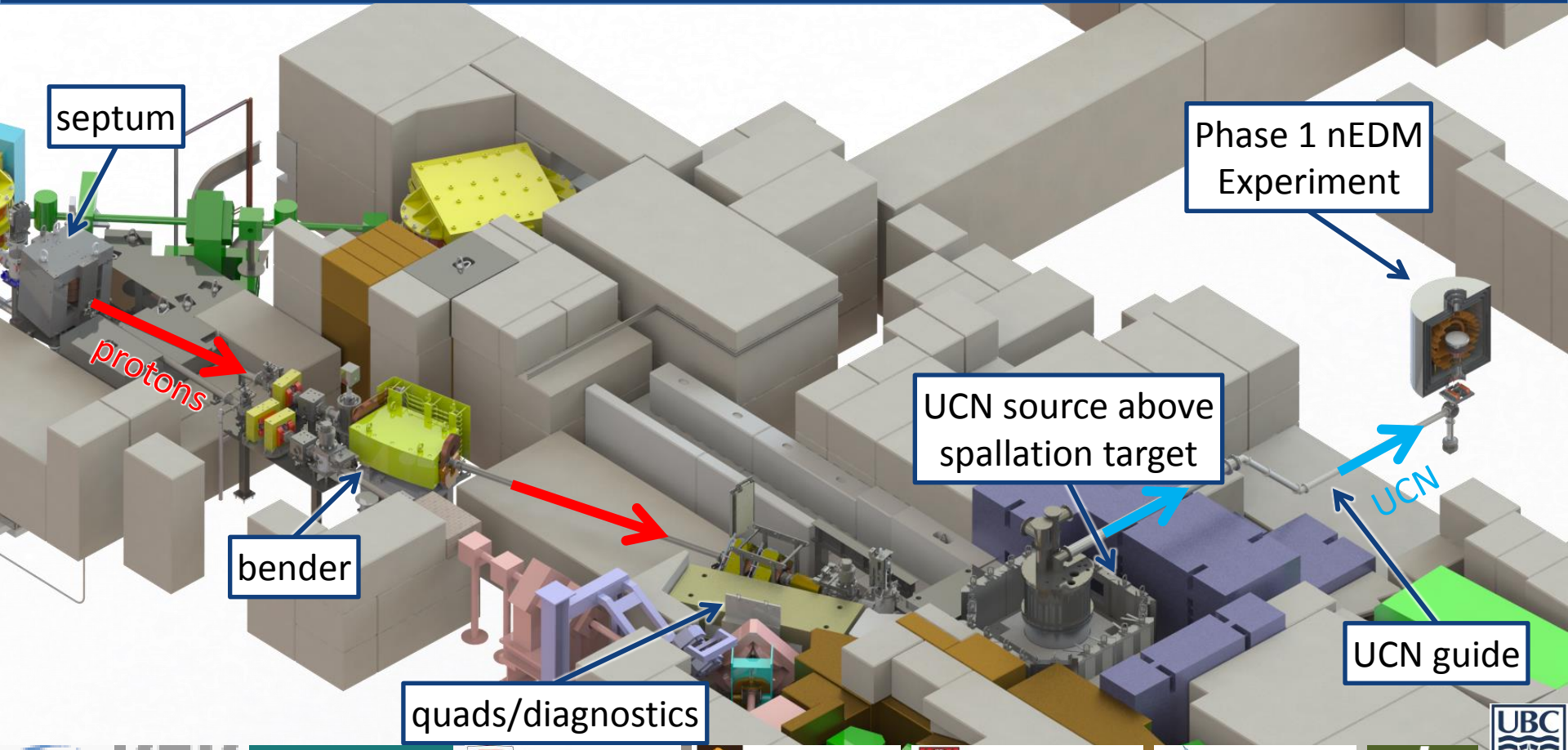

**Nordion**
commercial medical isotope production
3 cyclotrons

**Cyclotron**
500 MeV
350 μA

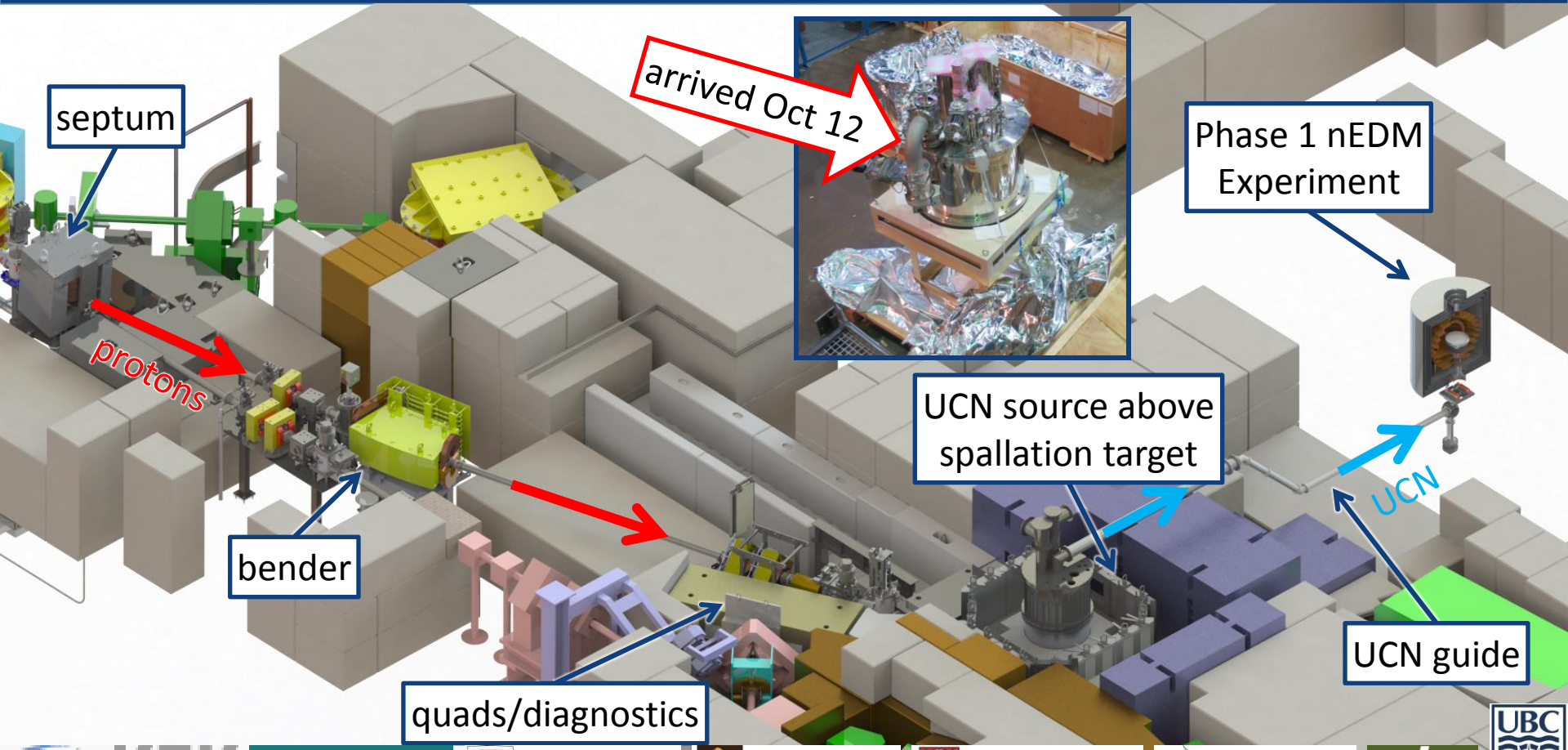
**Particle Physics**
Pienu
Ultra Cold Neutrons

**CMMS**
Centre for Molecular and Material Science (μSR)

# UCN Facility @ TRIUMF



# UCN Facility @ TRIUMF



# UCN Facility @ TRIUMF

First neutrons confirmed

arrived Oct 12

Phase 1 nEDM Experiment

UCN source above spallation target

UCN

protons on target: Nov 1

bender

quads/diagnostics

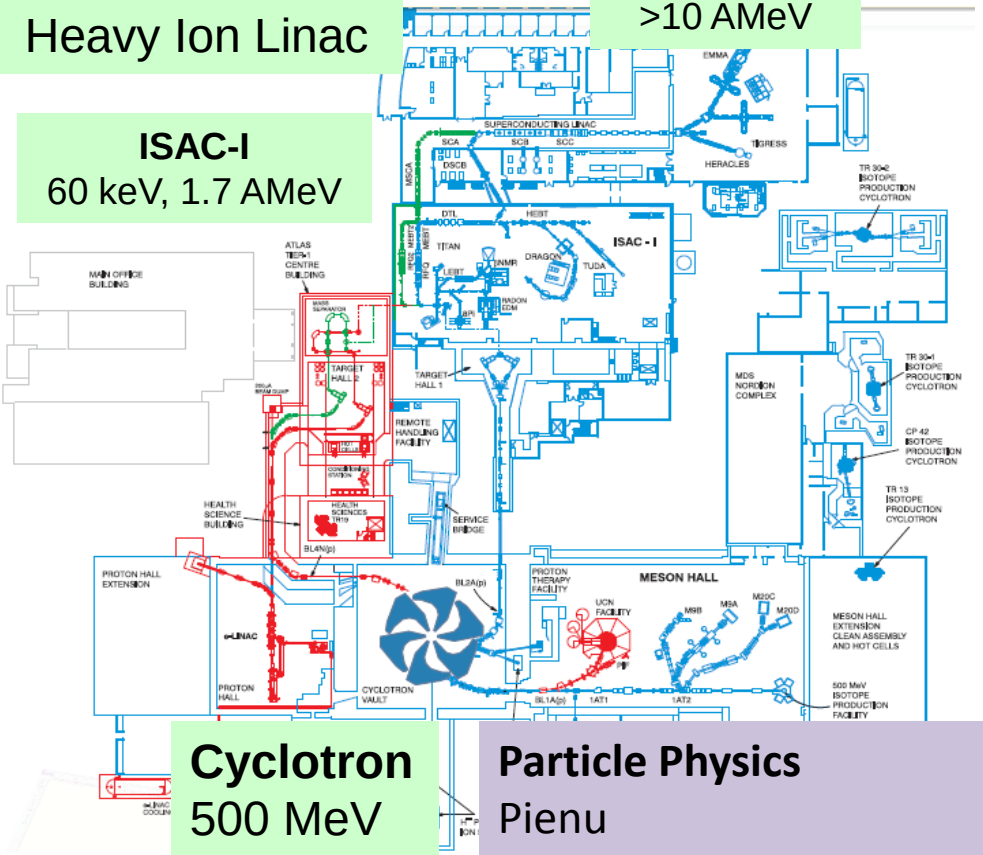
UCN guide

# TRIUMF's accelerator complex

40 MV SRF
Heavy Ion Linac

**ISAC-II**
>10 AMeV

**ISAC-I**
60 keV, 1.7 AMeV




**Cyclotron**
500 MeV
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**ISAC (Isotope Separator and ACcelerator)**
Rare Isotope Facility
- Nuclear Structure
- Nuclear Astrophysics
- Fund. Symmetries
- CMMS (βNMR)

**Nordion**
commercial medical isotope production
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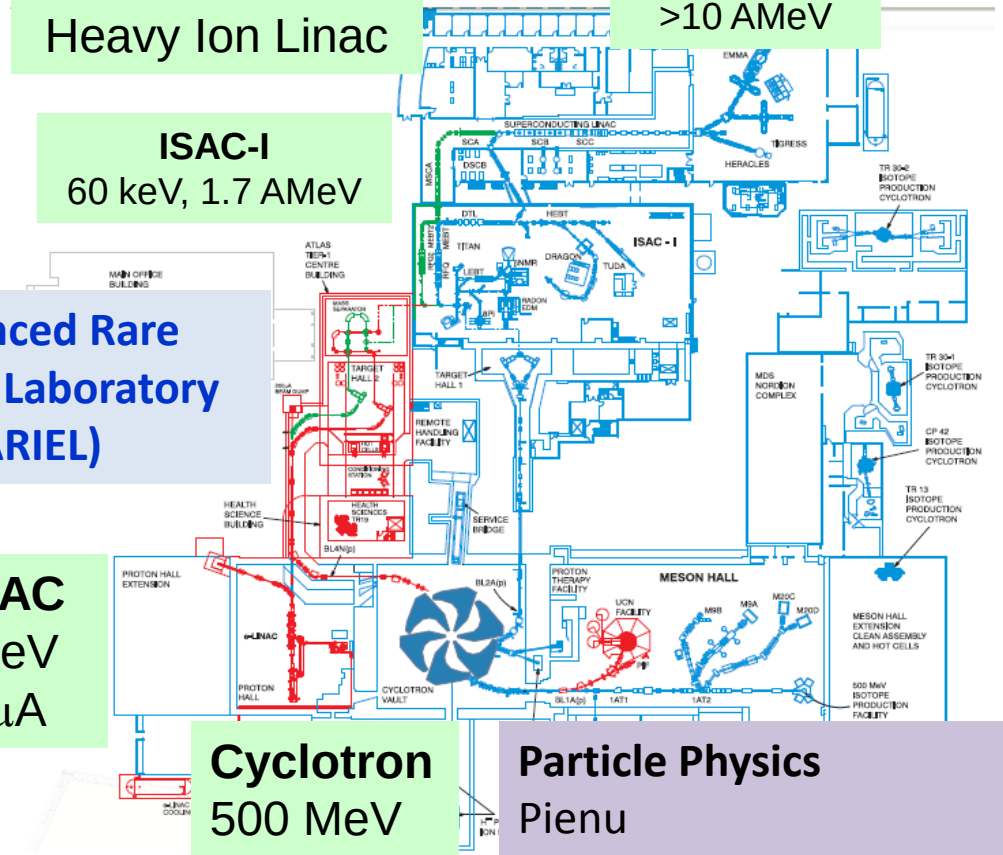



**Advanced Rare Isotope Laboratory (ARIEL)**

**eLINAC**
35 MeV
100 μA

**Cyclotron**
500 MeV
350 μA

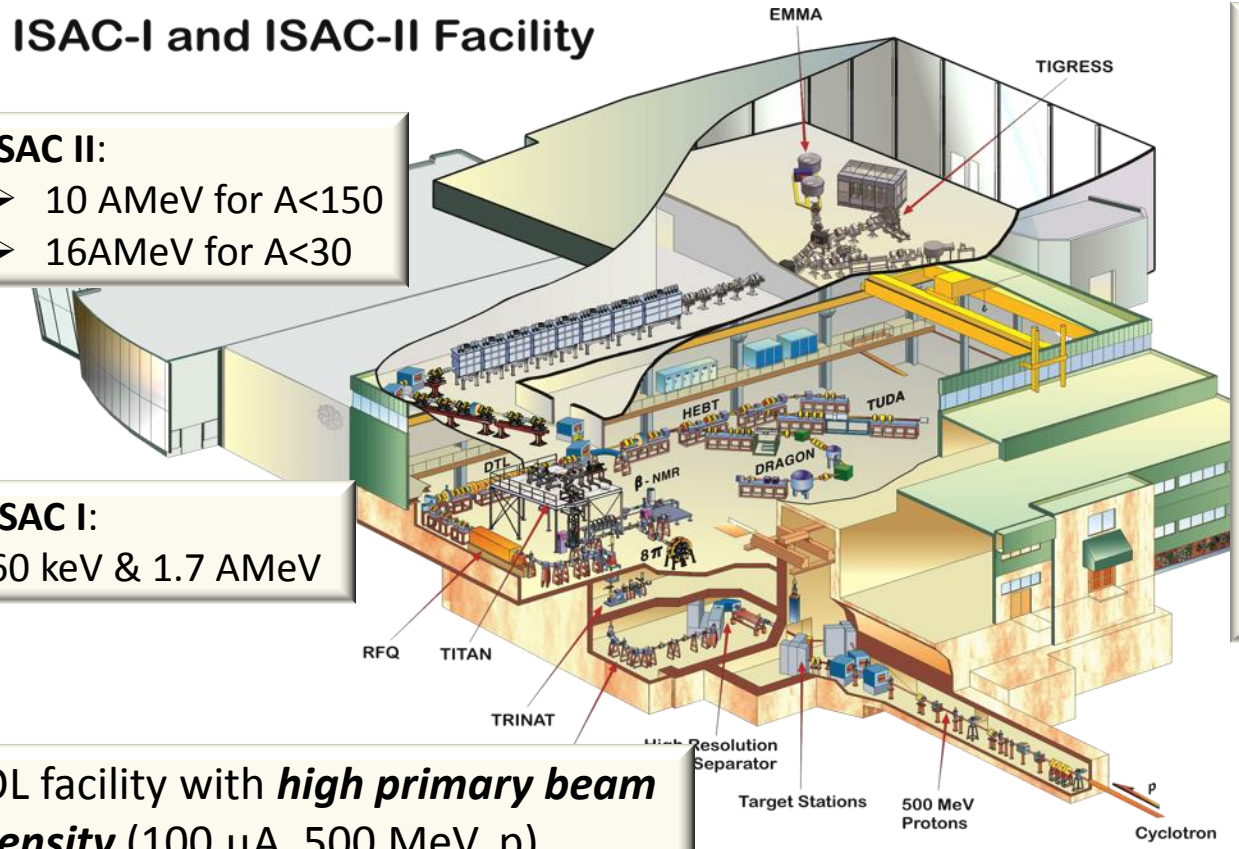
**Particle Physics**
Pienu
Ultra Cold Neutrons

**ISAC (Isotope Separator and ACcelerator)**
Rare Isotope Facility
- Nuclear Structure
- Nuclear Astrophysics
- Fund. Symmetries
- CMMS (βNMR)

**Nordion**
commercial medical isotope production
3 cyclotrons

**CMMS**
Centre for Molecular and Material Science (μSR)

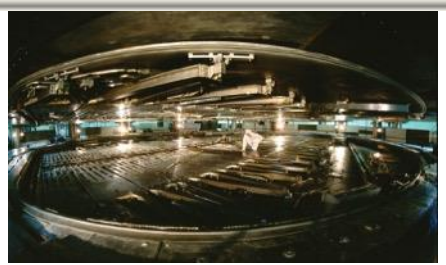
# ISAC rare isotope facility




**ISAC II**:
- 10 AMeV for A<150
- 16AMeV for A<30

**ISAC I**:
60 keV & 1.7 AMeV

Programs in
- Nuclear Structure & Dynamics
- Nuclear Astrophysics
- Electroweak Interaction Studies
- Material Science
- 18 permanent experiments

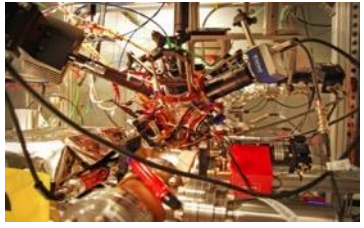


ISOL facility with ***high primary beam intensity*** (100 μA, 500 MeV, p) delivering RIBs since 1999.

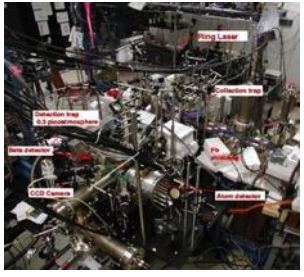
# ISAC experimental areas (low energy)

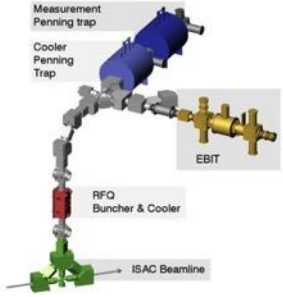
Low energy RIBs
< 60 keV

## FRANCIUM MOT
(PNC, anapole moment)



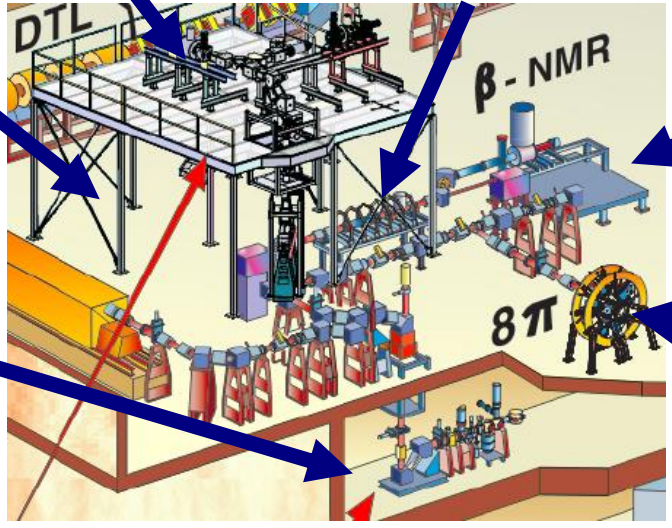
## TRINAT
Neutral Atom Trap
(βν-neutrino correlations)





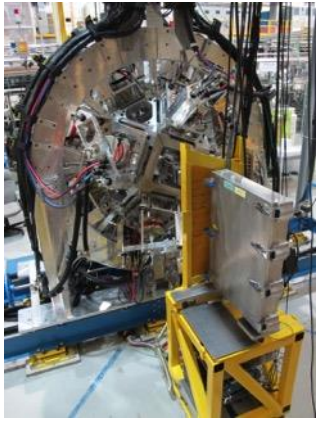

## TITAN
Penning Traps
(masses,
in-trap decay)

## Polarizer beamline
Laser spectroscopy, MTV
CPT test, betaNMR

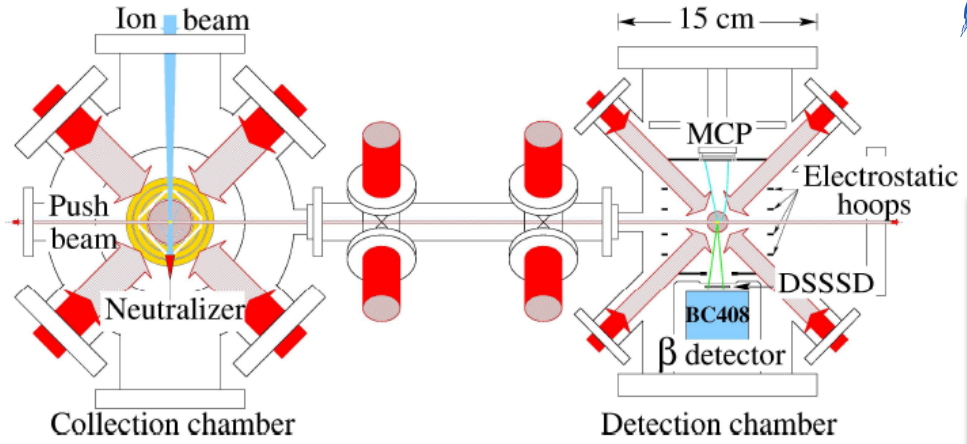



## Beta-NMR
Material science

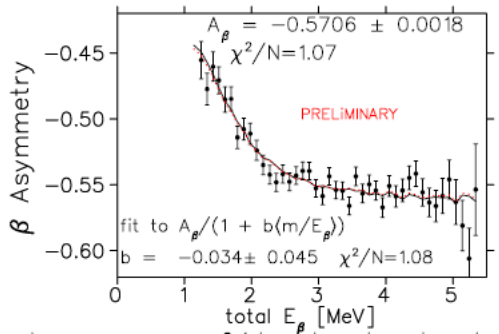
## GRIFFIN
Gamma & Electron
spectrometer
(decay spectroscopy,
superallowed decays)

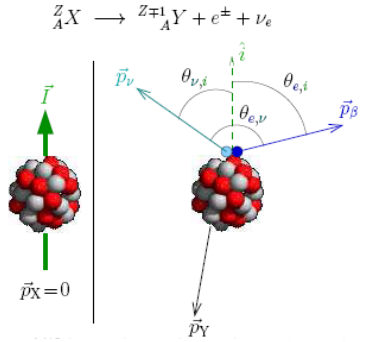


# TRINAT: beta-neutrino correlation experiment




Traps provide a backing-free, cold ($\lesssim 1$ mK), localized ($\lesssim 1\ \mathrm{mm}^3$) source of short-lived radioactive atoms




TRIUMF | TEXAS A&M UNIVERSITY | UNIVERSITY OF MANITOBA | TEL AVIV UNIVERSITY

Atom trap: electro-weak study to probe S/V/T interactions using β-ν correlations.

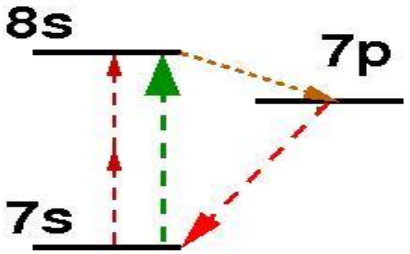
- TAMU PhD 2016 B. Fenker
- best $A_\beta$ accuracy measurement in a nucleus or neutron
- complementary sensitivity to LHC for 4-fermion contact interaction.

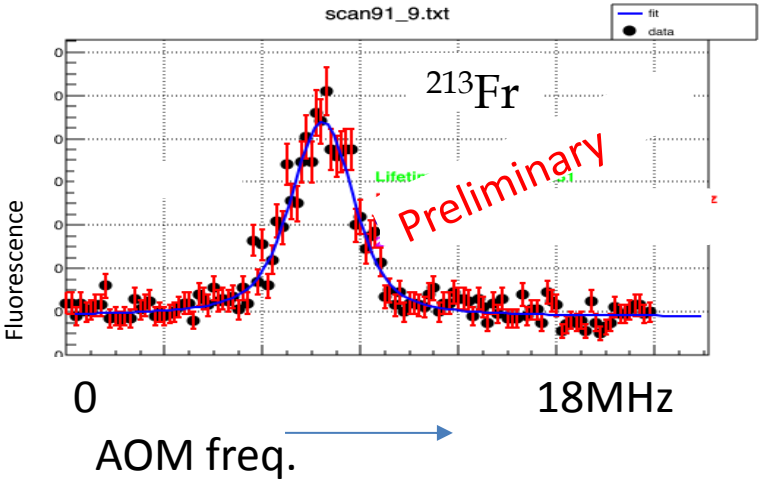
- Submitted to PRL

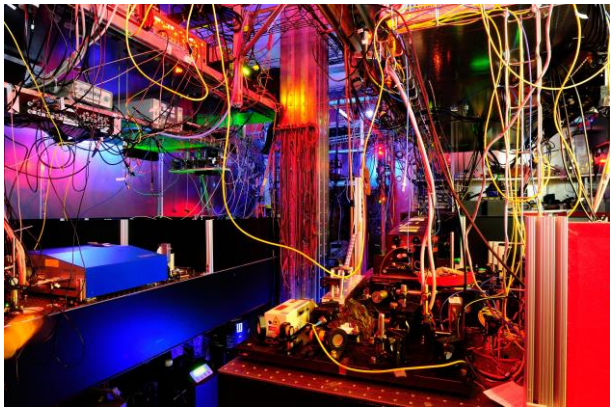
# Fr parity violation atom trap experiment

Atom trap experiment for tests of parity non-conservation and searches for an anapol moment in Fr isotopes.

- Observed for the first time the 7s-8s transition (the parity-violating transition) using two-photon spectroscopy
- Demonstrated DC Stark shift of the 7s-8s transition
- Major milestone!
- Neutralizer worked well
- Science trap operational
- Submitted to PRL



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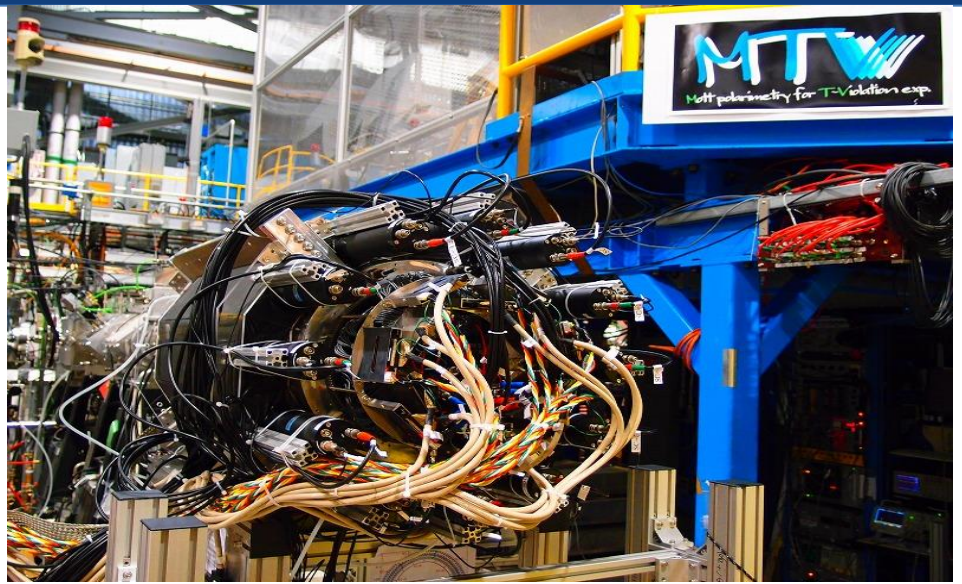
UNIVERSITY OF MANITOBA

# MTV experiment

## S1183-MTV : Test of time reversal symmetry using polarized unstable nuclei: $^{8}$Li

Motivation : Searching T-Violating Transverse Electron Polarization in polarized Li-8 beta decay
T & P violating same as EDM, but in different system
Physics beyond the Standard Model : Predicted by
R-parity violating MSSM, lepto-quarks, compositeness




Polarized Li-8 : TRIUMF-ISAC

$10^{7}$pps @ 80% polarization

+

Transverse Electron Polarimeter :
Mott Analyzer using Cylindrical Drift Chamber

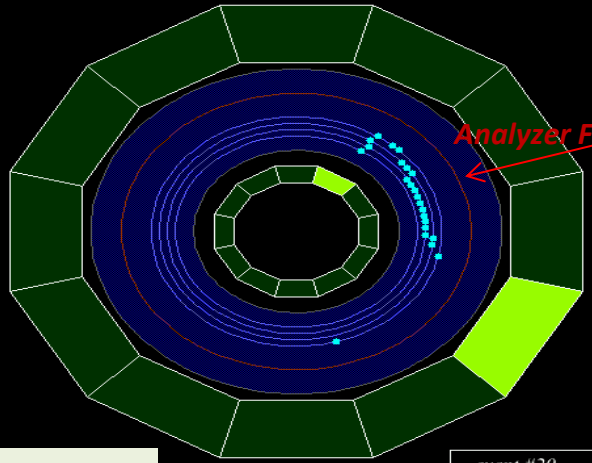
50MHz Mott-Scattering Tracking Measurement

→ Highest Precision Test of T-violating correlation parameter R ~ $10^{-4}$

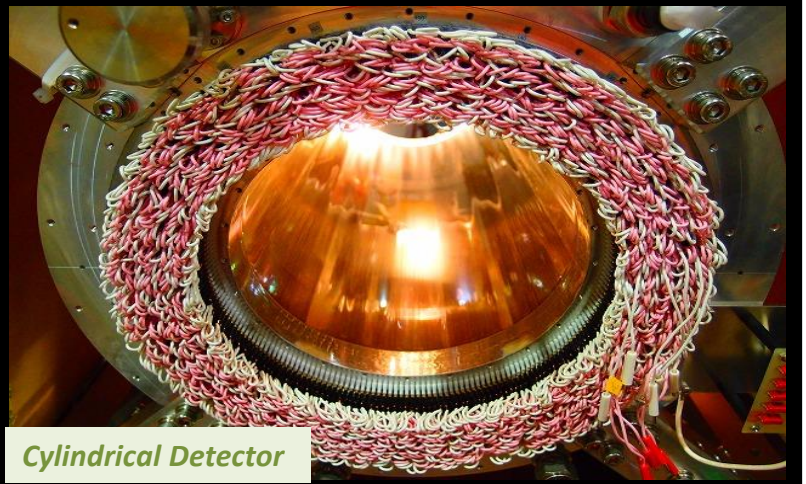
Previous Test at PSI 2003 $R_{PSI} = (-0.9 \pm 2.2) \times 10^{-3}$

MTV
Mott polarimetry for T-Violation exp.

Run-IV 2012




Scattering Event



Cylindrical Detector

KEK

**2008 Test Experiment at KEK-TRIAC**

***R*~40%** with 8% pol., $10^5$pps

TRIUMF

KEK to TRIUMF

**2011 – 2012 CDC Commissioning**
**2013 – 2015 Systematics Tests**
**2016 – 2017 Physics Production to 0.01% precision**

**Expected Physics from upcoming runs (2017)**
1. First observation of non-zero *R* at final state interaction precision.
2. First measurement of nuclear *correlation (transverse polarization).*
3. Lorentz violation tests in weak interaction.

SAINT PAUL'S UNIVERSITY TOKYO MDCCCLXXIV

立教大学
RIKKYO UNIVERSITY

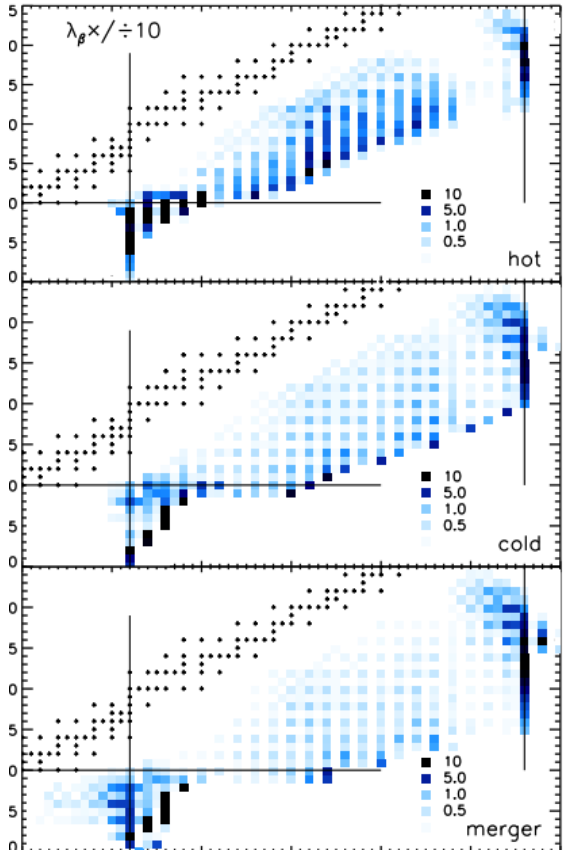
RIKEN

TOHOKU UNIVERSITY

NAGOYA UNIVERSITY

TRIUMF

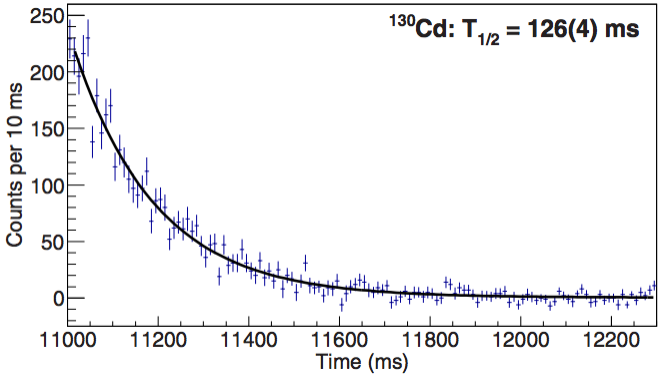
# GRIFFIN: $^{128,129,130}$Cd β-decay




PHYSICAL REVIEW C 93, 062801(R) (2016)

RAPID COMMUNICATIONS

## Half-lives of neutron-rich $^{128-130}$Cd




Measurement of decay half lives and properties are important for astrophysical r-process calculations

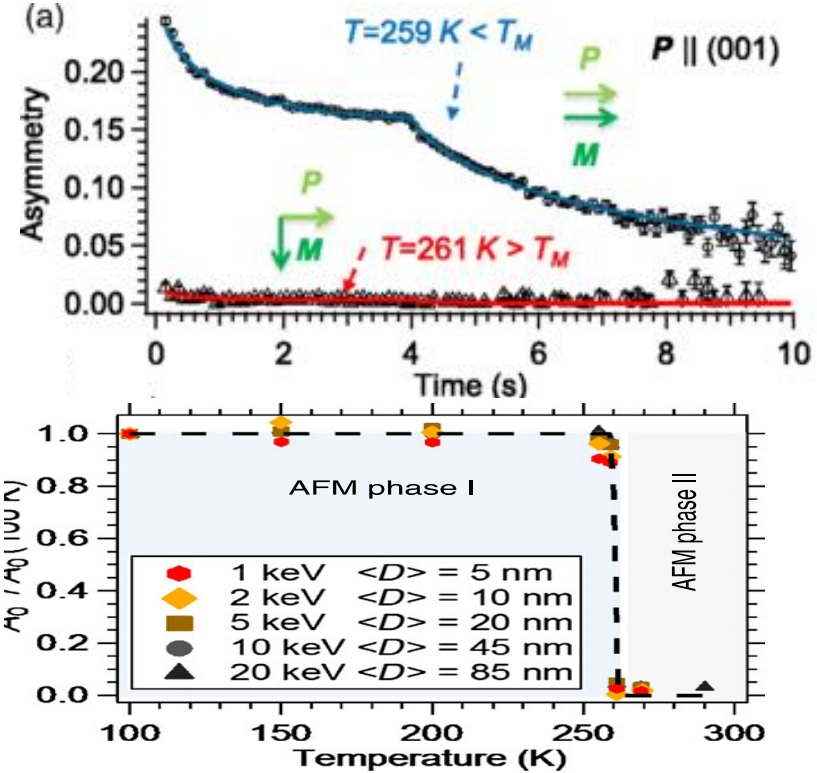
G. Lorusso et al. PRL 114 192501 (2015)

M. Mumpower *et al.*, Prog.Part.Nucl.Phys. 86, 86 (2016)

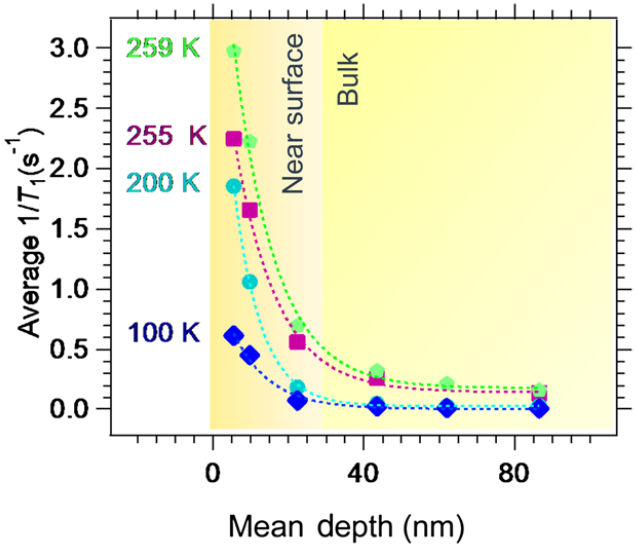
# β-NMR Investigation of the Depth-Dependent Magnetic Properties of an Antiferromagnetic Surface

PRL **116**, 106103 (2016) PHYSICAL REVIEW LETTERS week ending 11 March 2016

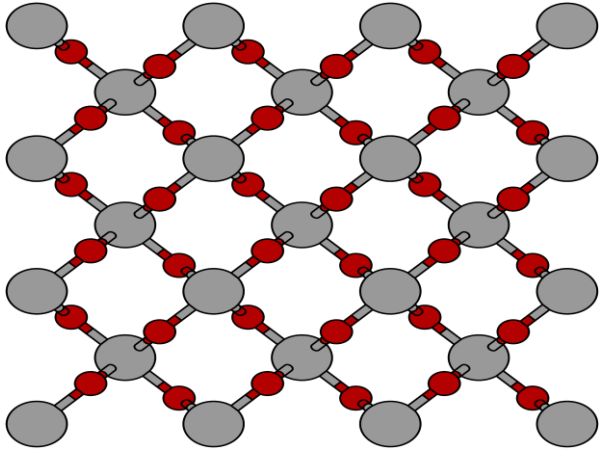
D. L. Cortie, T. Buck, M. H. Dehn, V. L. Karner, R. F. Kiefl, C. D. P. Levy, R. M. L. McFadden, G. D. Morris, I. McKenzie, M. R. Pearson, X. L. Wang, and W. A. MacFarlane

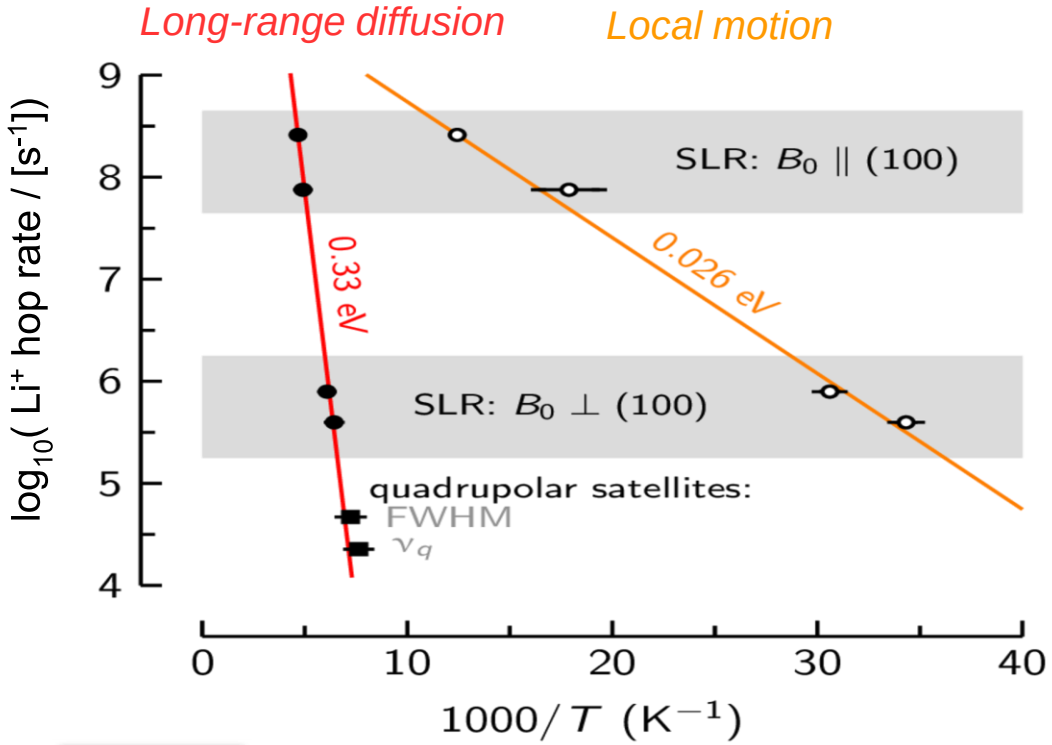



β-NMR was used to study the depth dependence of the Morin spin reorientation transition in α-$Fe_2O_3$ (hematite). The surface-localized dynamics decay towards the bulk with a characteristic length of 11 nm, indicating the presence of soft surface magnons.



$Li^+$ dynamics in rutile $TiO_2$:
solving a long-standing mystery






Rutile $TiO_2$: a candidate electrode for solid-state lithium-ion batteries. Detailed studies on ionic motion and diffusion behavior.

Publication: R. McFadden (UBC chem) PRL in prep

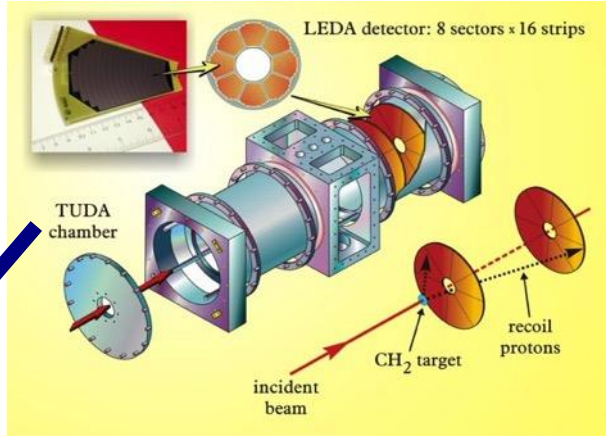
McMaster University
UNIVERSITY OF WOLLONGONG AUSTRALIA
a place of mind UBC CHEMISTRY
PHYSICS ASTRONOMY
UNIVERSITY OF ALBERTA
MAX-PLANCK-INSTITUT FÜR FESTKÖRPERFORSCHUNG

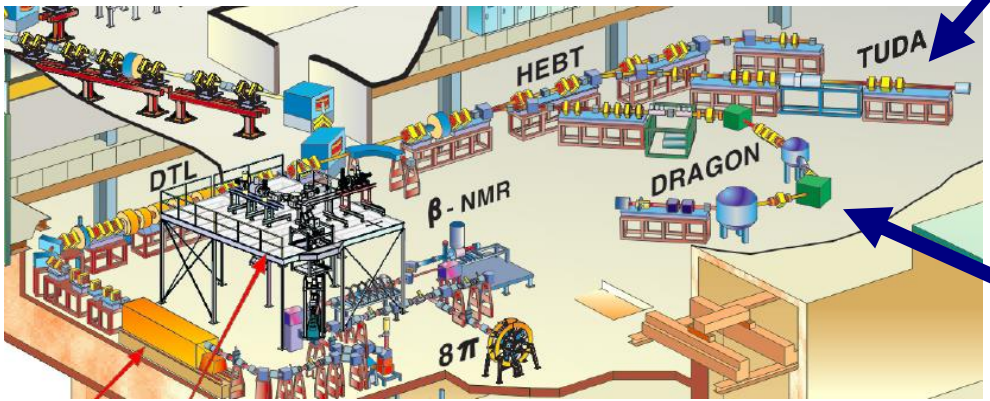
# ISAC experimental areas

*Medium energy RIBs*
*~ 0.15 -1.7 AMeV*

## TUDA

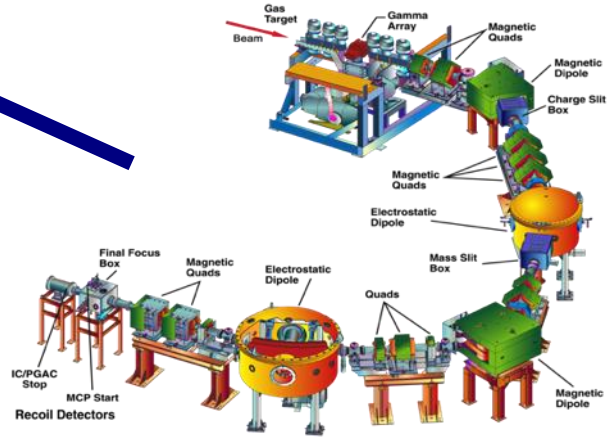
Astrophysical charged particle reactions



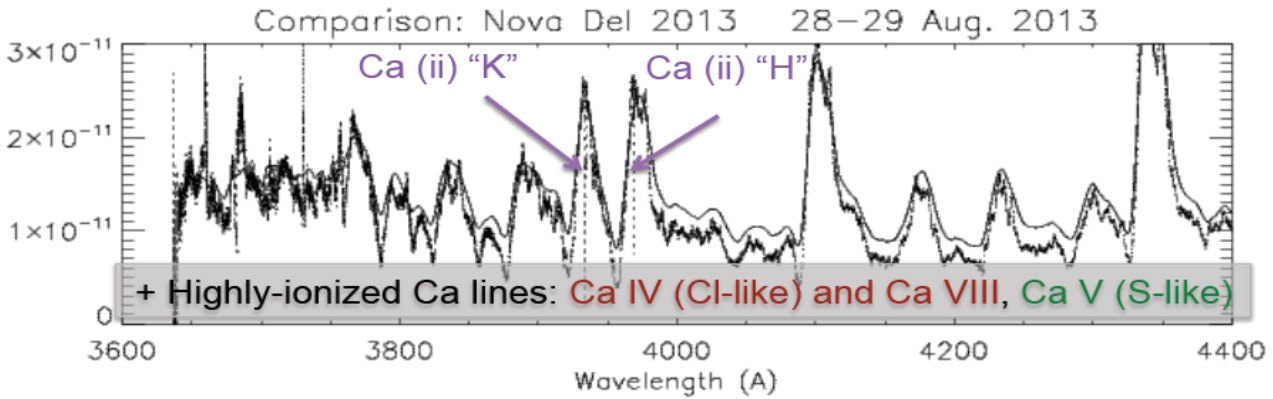

## DRAGON

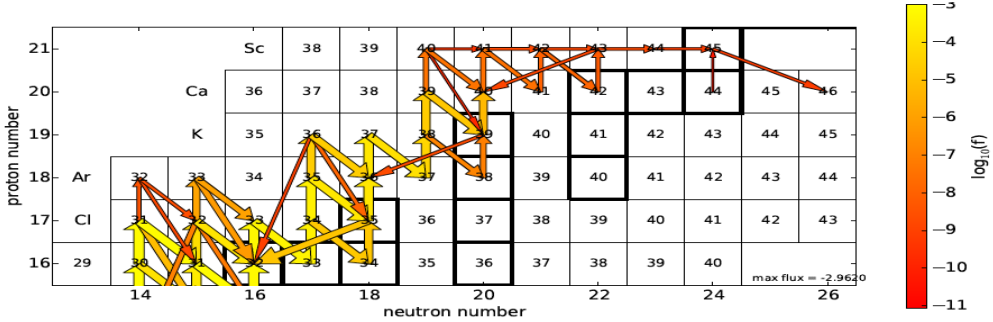
Astrophysical capture reactions



# The $^{38g}K(p,\gamma)^{39}Ca$ reaction at DRAGON

- Calcium, potassium, argon have been observed (visible, UV, IR) in expanding nova shells
- Abundances of calcium exceed model predictions
- Ca is supposed to be the “end point” of nucleosynthesis in novae




NuGrid network calculations with UVic, TRIUMF et al.

- $^{38g}K(p,\gamma)^{39}Ca$ reaction uncertainty affects Ar-K-Ca abundances by factors x25, x136, x58 respectively

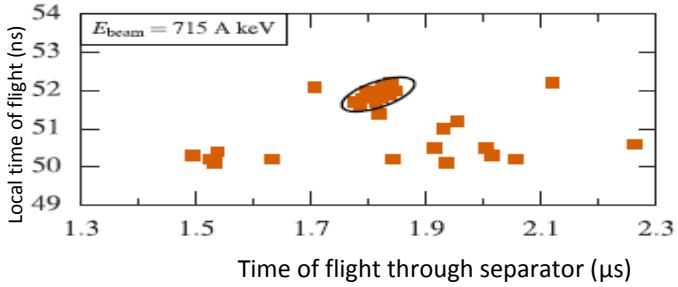
# The $^{38g}K(p,\gamma)^{39}Ca$ reaction at DRAGON

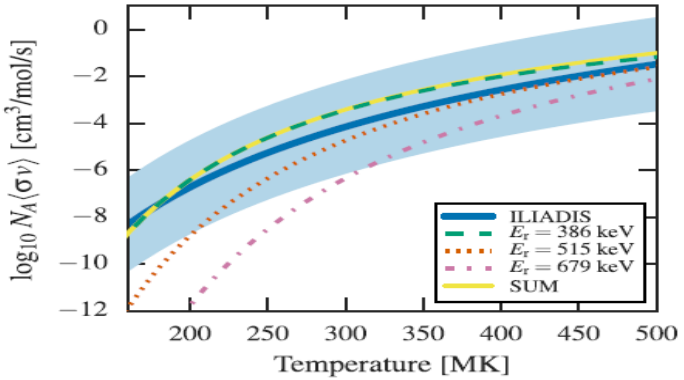
- Measurement at DRAGON recoil separator
- using 2 x $10^7$ $s^{-1}$ $^{38g}K$ beam from ISAC
- Uncertainty in Ar-K-Ca ejected abundances reduced by order of magnitude in model
- Highest RIB mass direct measurement of radiative capture

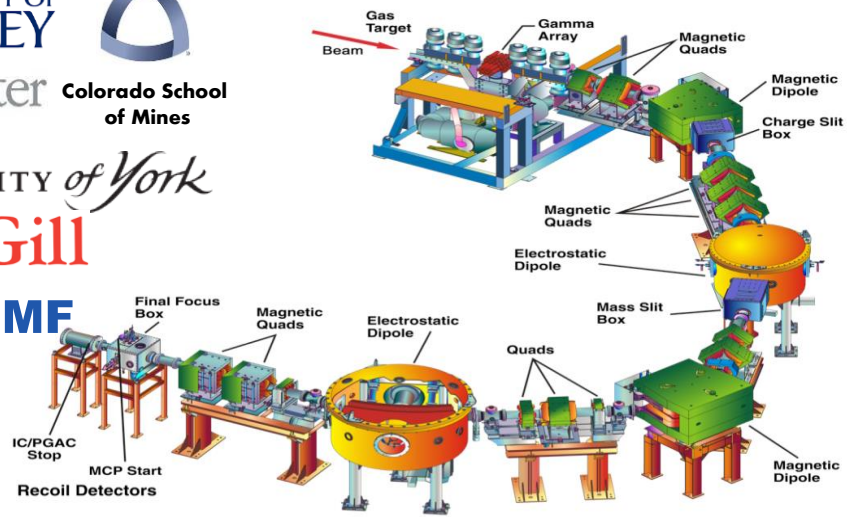
PRL 116, 132701 (2016) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2016

**Direct Measurement of the Astrophysical $^{38}K(p,\gamma)^{39}Ca$ Reaction and Its Influence on the Production of Nuclides toward the End Point of Nova Nucleosynthesis**

G. Lotay,[1,2,*] G. Christian,[3,†] C. Ruiz,[3] C. Akers,[3,4,‡] D. S. Burke,[5] W. N. Catford,[1] A. A. Chen,[5] D. Connolly,[6] B. Davids,[3] J. Fallis,[3] U. Hager,[6,§] D. A. Hutcheon,[3] A. Mahl,[6] A. Rojas,[3] and X. Sun[3,7]



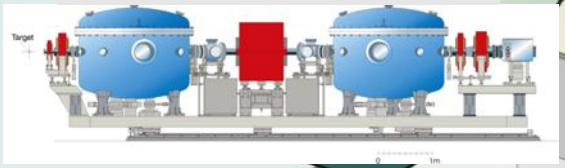



# ISAC experimental areas

High-energy RIBs
> 6 AMeV

**EMMA (2016)**
Mass analyzer for nuclear reactions

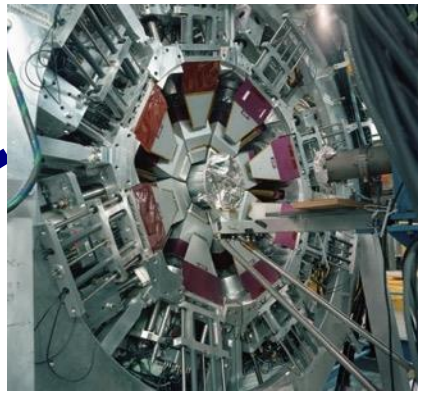




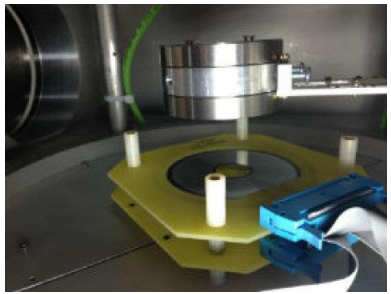
**IRIS**
Solid hydrogen target for direct nuclear reactions

**TIGRESS + auxiliary detectors**

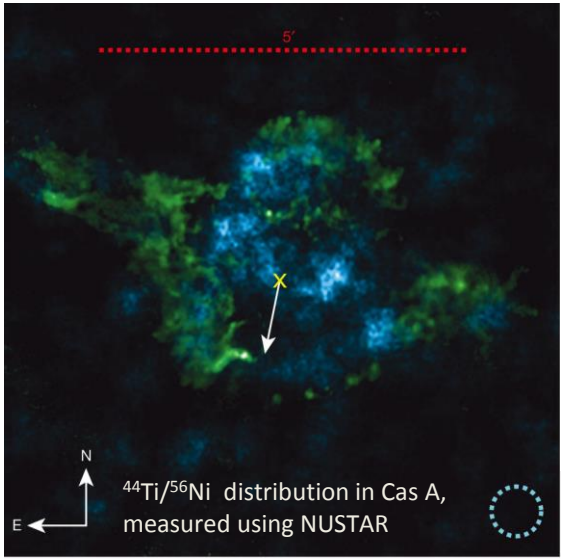
HPGe ɣ-ray spectrometer
in-beam spectroscopy of nuclear reactions

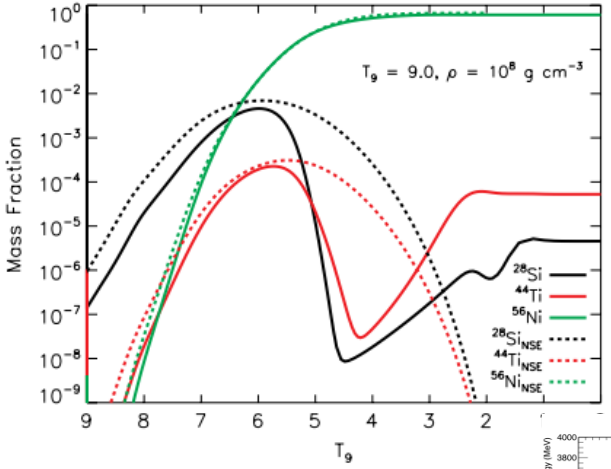


**TUDA II**
Scattering array for direct reactions



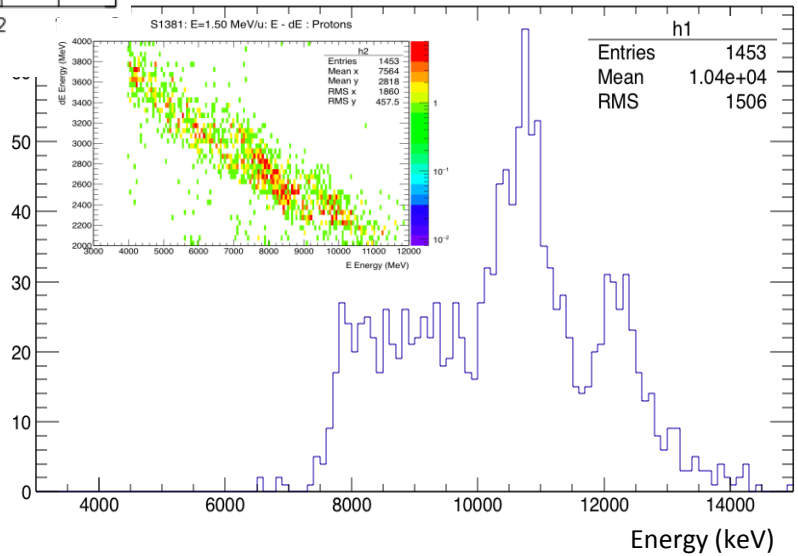
# Direct measurement of $^{21}$Na($\alpha$,$p$)$^{24}$Mg at TUDA




- $^{44}$Ti production in core-collapse SNe
- Affected by $^{21}$Na($\alpha$,$p$)$^{24}$Mg reaction in alpha-rich freeze-out
- Measured with TUDA facility and $^{21}$Na beam
- Data taken July 2016 → under analysis

S1381: E=1.50 MeV/u: Total Energy : Protons



# The **A**dvanced **R**are **I**sotop**E** **L**aboratory will triple TRIUMF's isotope beam capacity

- Uses state-of-the-art, made-in-Canada super-conducting electron linear accelerator technology; targets are designed to allow medical isotopes to be extracted alongside the experimental program
- Represents ~$100 million investment by federal and provincial governments; supported by 19 university partners from across Canada
- Project to occur in two phases:
  - ARIEL-I completed in Fall 2014;
  - ARIEL-II funded by Canada Foundation of Innovation, funding now secured.
- Will provide more and new isotopes

TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY

# The goal of ARIEL: science and opportunities

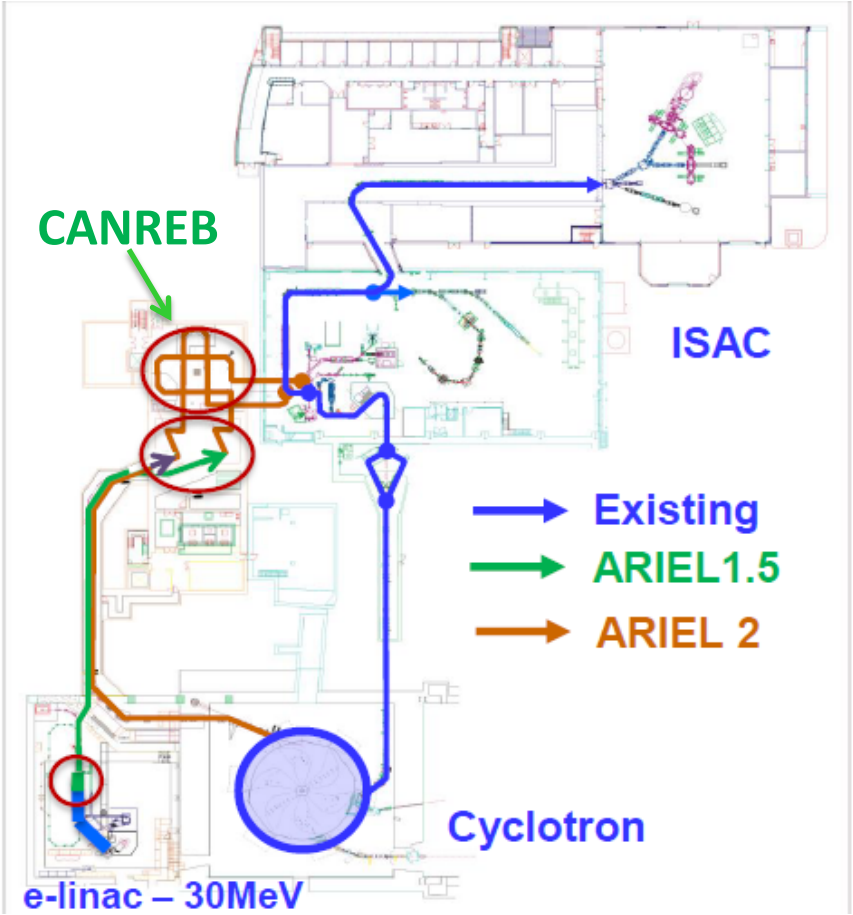
ISOTOPES

- **What we can do at ARIEL:**

- **isotopes for characterizing new materials:**
  - **$^{8}$Li as a sensitive probe for interfaces**
- **medical isotopes for nuclear imaging and tumor treatment:**
  - **alpha-emitters like $^{211}$At**
- **isotopes for developing and refining theory for nuclear physics**
  - **Proton- and electron-induced rare isotopes at the extremes**
- **isotopes as laboratories to search for new symmetries in nature**
  - **Heavy proton-induced isotopes, like Fr, Rn and some light electron-induced isotopes: Li**
- **isotopes: how and where the heavy elements were produced in the universe**
  - **Very neutron rich isotopes from photo-fission**

- **Triple the available beam time: more time for beam developments**

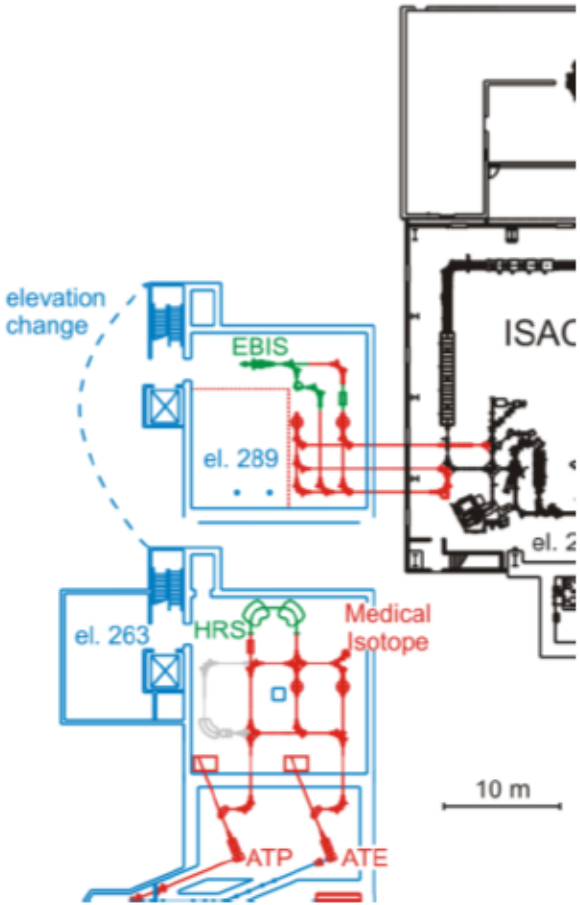
# Status of ARIEL project




TRIUMF ARIEL

ADVANCED RARE ISOTOPE LABORATORY

- ARIEL1.5
  - Complete beamline to ARIEL electron target station – parts in hand - integrate to the ARIEL2 schedule
  - Complete e-Linac to final 30MeV (ACMuno->ACMduo)
- ARIEL2
  - Target ion source
  - Target hall infrastructure – hot cell design
  - Low energy beam transport (with CANREB) – detailed design of beamline completed
    prototype beam line under construction
- CANREB
  - High resolution separator
  - Beam preparation with RFQ and EBIS

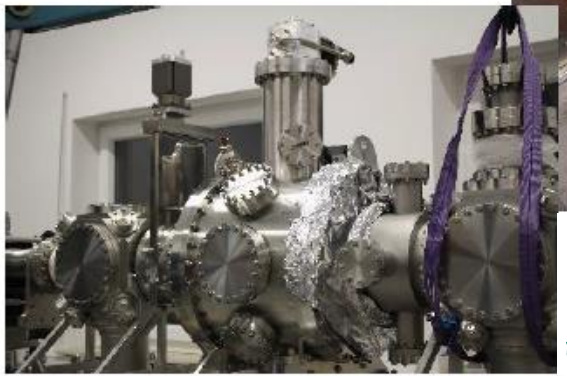



## Main components of CANREB:

- high resolution mass separator M/ΔM = 20,000 for beams from ISAC and ARIEL
- charge state breeder A/q 5 - 7
  - RFQ cooler/buncher
  - EBIS charge state breeder
  - Nier spectrometer for highly charged ions
  - Connect ISAC beam to CANREB

# CANREB status

- High resolution separator being machined by D-pace/Buckley
- Radio Frequency Quadrupole (RFQ) buncher engineering drawings in workshop
  - Accept intense beams from ARIEL targets
  - Low emittance and low energy spread as well as bunched beams for EBIS injection
- Pulse Drift Tube (PDT) for energy matching → HV tested
- Electron Beam Ion Source (EBIS) being assembled by MPI Heidelberg
- Nier separator dipole being designed by Danfysik



MAX-PLANCK-INSTIT FÜR KERNPHYSIK

# ARIEL Completion to Science

| year | |
|---|---|
| 2020 | ISAC-CANREB-ISAC beams |
| 2022 | ARIEL beam (Li-8) |
| 2022 | ARIEL photo-fission beams to ISAC |
| 2023 | ARIEL spallation beams to ISAC |

**ARIEL user consultation process: town-hall meeting January 10 2017**

TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY





# Conclusions

ISAC is doing well, many results, and controlling reliability and new developments

ARIEL/ISAC will enable the delivery of three parallel radioactive beams to users:

- Two cyclotron-beams for proton-induced reactions, up to 100 kW
- One electron linac beam, up to 100 kW, 35 MeV
  - Photo-fission elements of n-rich beams, astrophysics, nuclear physics
  - Li-beams for βNMR and many other material sciences opportunities

ARIEL will be a multi-user radioactive beam facility:

- Up to three independent experiments
- More time for beam developments

Excellent progress, all funding now secured:

- Photo-fission target developments under way
- e-beam beam lines on track
- Proton beam line in preparation
- User consultation on-going, considering reduced ISAC on-line operation

TRIUMF

Canada's national laboratory for particle and nuclear physics

Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

# Thank you!
# Merci!

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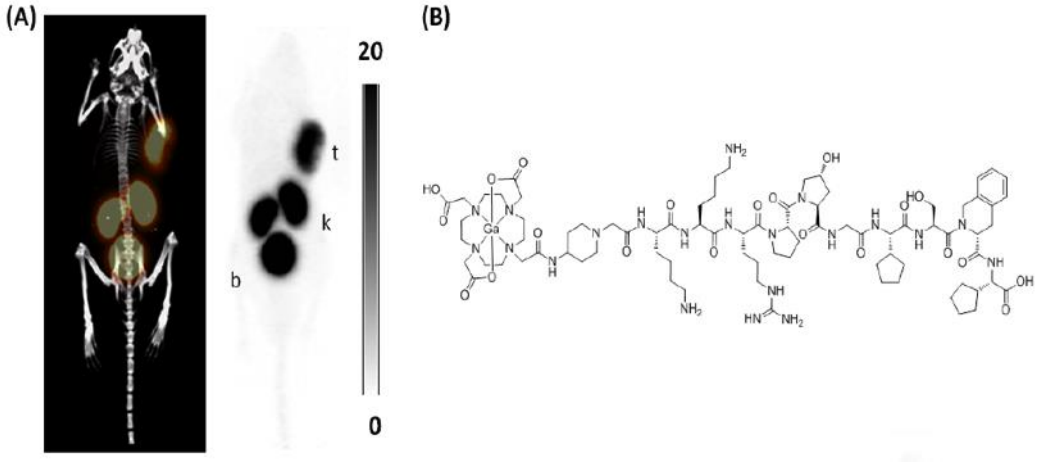
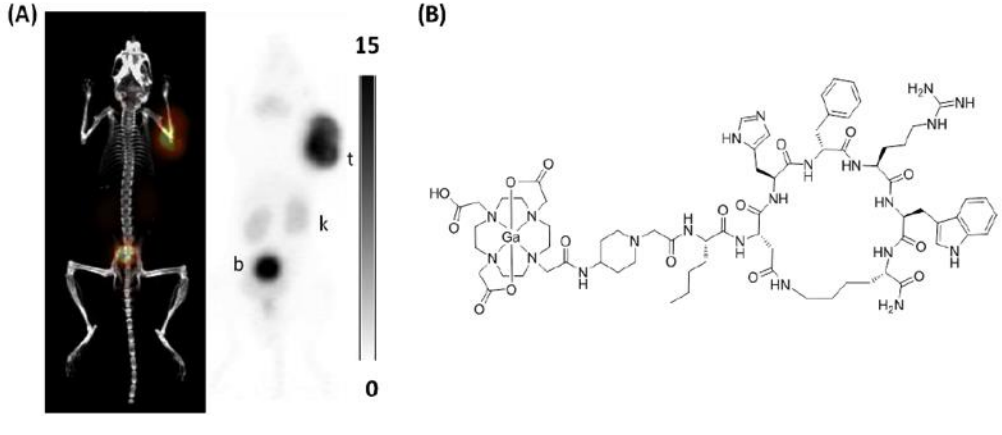
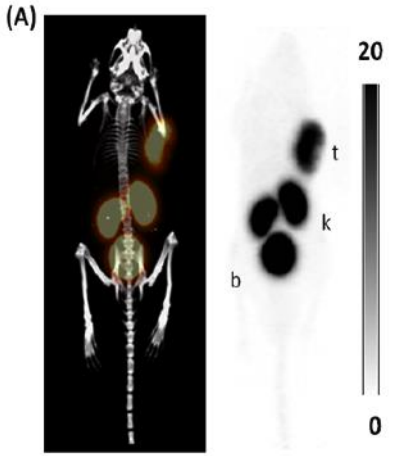
# Isotopes for medical application: tumor treatment and imaging




Purpose: Design new therapeutic radiopharmaceuticals for the treatment of advanced, incurable forms of skin, breast and prostate cancers

# Isotopes for medical application: tumor treatment and imaging

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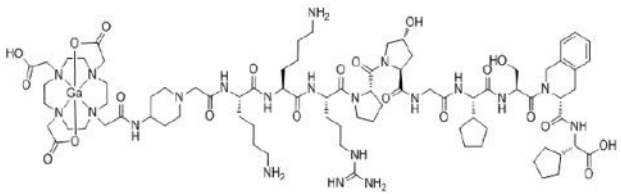

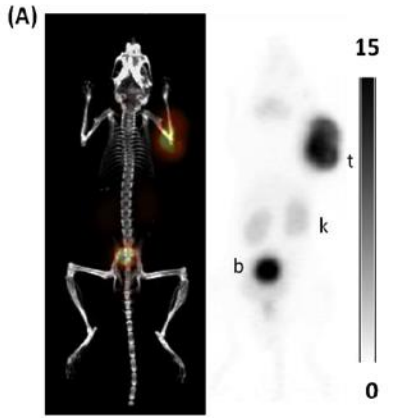


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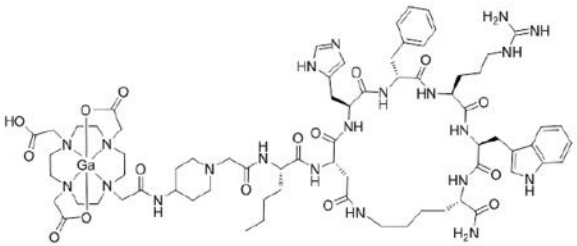

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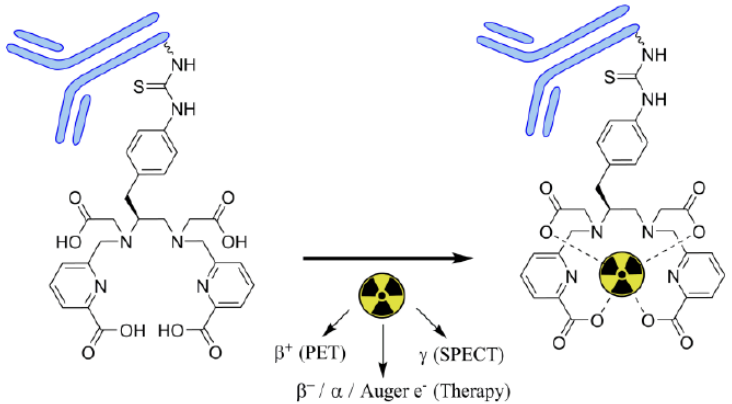
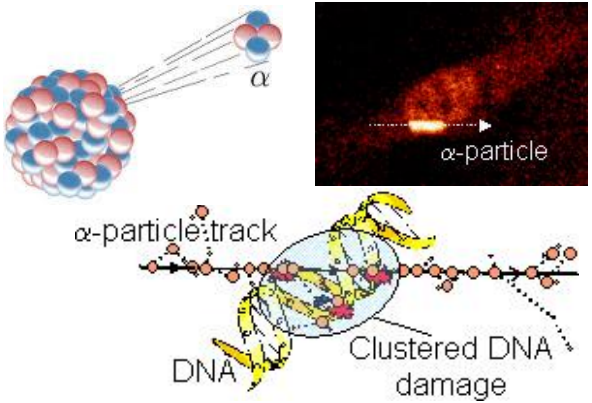



Alpha emitting isotopes: powerful way for direct tumor treatment

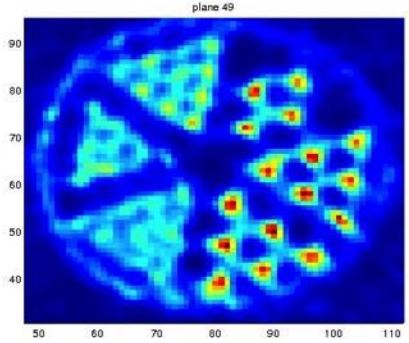
## Alpha emitting isotopes: powerful way for direct tumor treatment




Clustered DNA damage due to
'heavy particle' stopping power, short range.

**$^{211}$At particularly well suited for applications**
**Study surrogate functionality of $^{209}$At for imaging**

**First image with ISAC isotopes**




$^{211}$At is generated via
$^{211}$Rn at ISAC and ARIEL via
protons and could be 'exported'
across Canada.