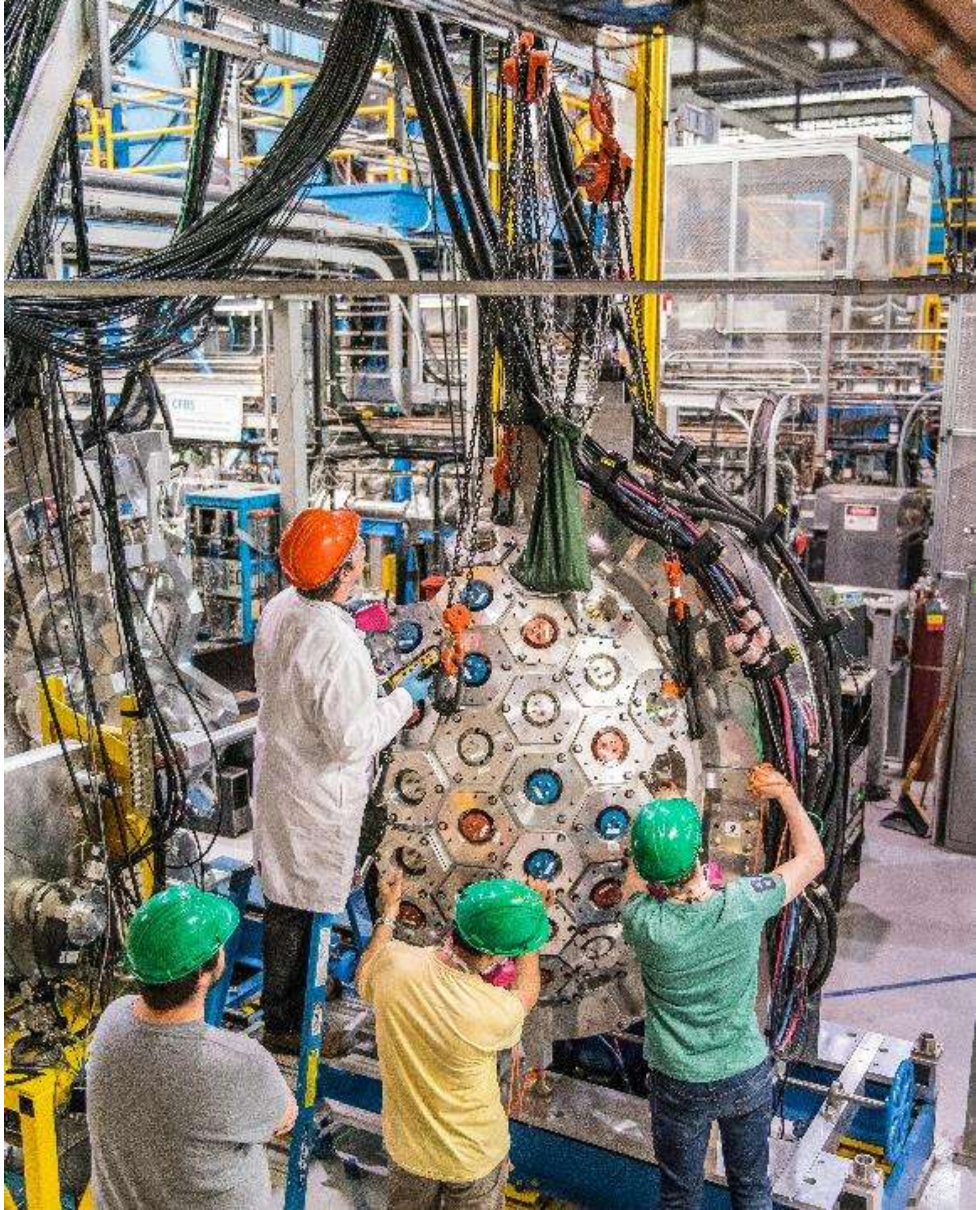
TRIUMF

Nuclear Physics: From ISAC to ARIEL

A.A. Kwiatkowski
Research Scientist
Science Week, 17 August 2020



Discovery, accelerated

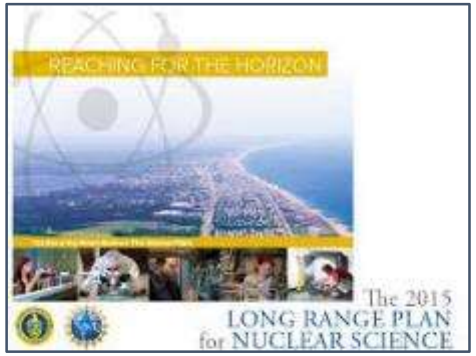
ISAC-TRIUMF is a world-class platform for research excellence.

Nuclear-physics program is built around the questions from the Canadian Subatomic Physics Long Range Plan: - Tuesday

- **Nuclear Structure & Dynamics**
  - How do quarks and gluons give rise to the hadronic properties and the phases of hadronic matter?
  - How does the structure of nuclei emerge from nuclear forces?
- **Nuclear Astrophysics**
  - How are the elements formed in the Universe?
- **Precision Tests of Fundamental Interactions**
  - What is the nature of physics at the electroweak scale and beyond?
  - What is the nature of neutrino masses?
  - (Franke, Mon)

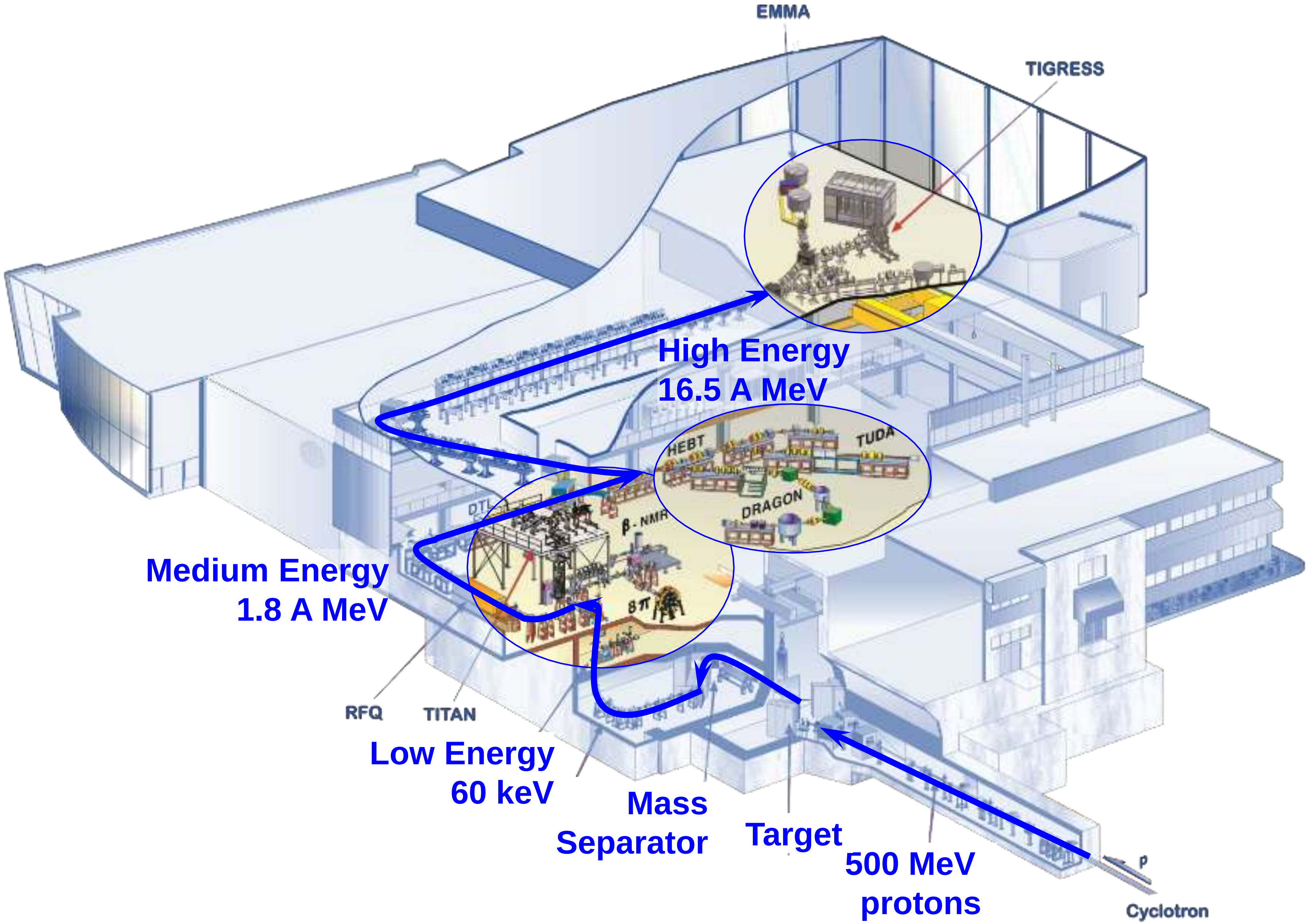
Huber & Roney

Lewitowicz



Halman

All RIB experiments within Canada occur at ISAC-TRIUMF.



High-energy experiments focus on reactions & excited states.

Nuclear Astrophysics
Fundamental Interactions
Nuclear Structure & Dynamics

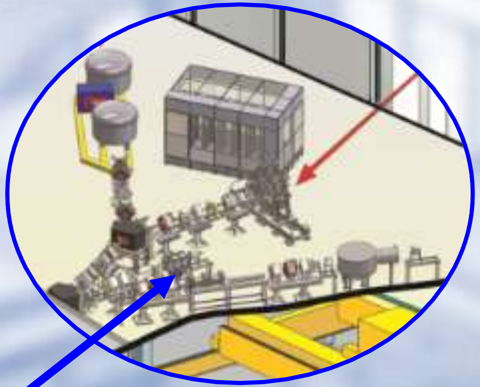

C. Andreoiu
SFU

A. Chen
McMaster

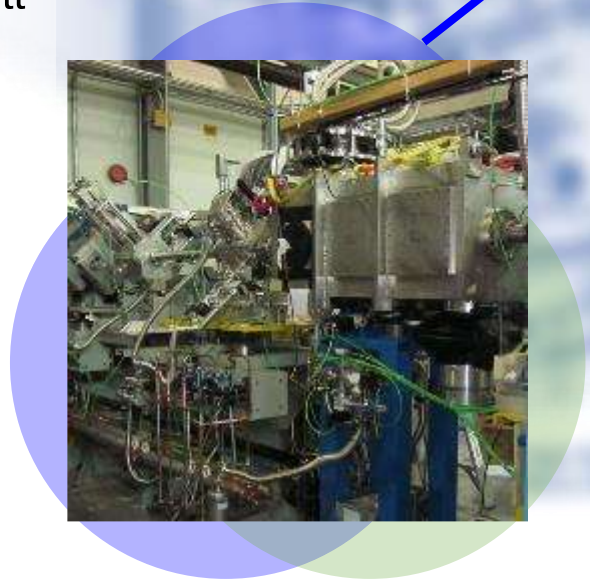

G. Christian
St. Mary's

R. Kanungo
St. Mary's/TRIUMF

P.E. Garrett
Guelph



IRIS
Solid hydrogen target
Transfer reactions





M. Alcorta
B. Davids
G. Hackman


R. Kruecken
C. Ruiz

High-energy experiments focus on reactions & excited states.

I. Dillmann
A. Garnsworthy


G. Hackman
R. Kruecken
G. Ball

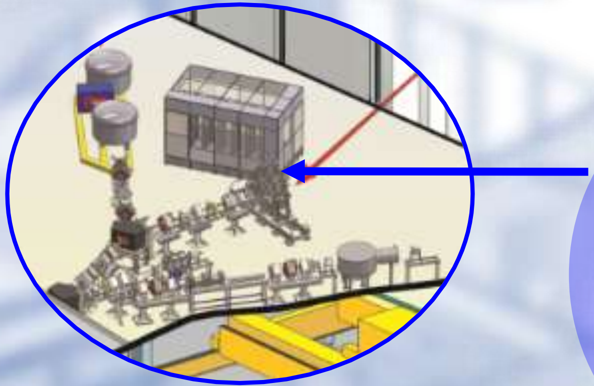


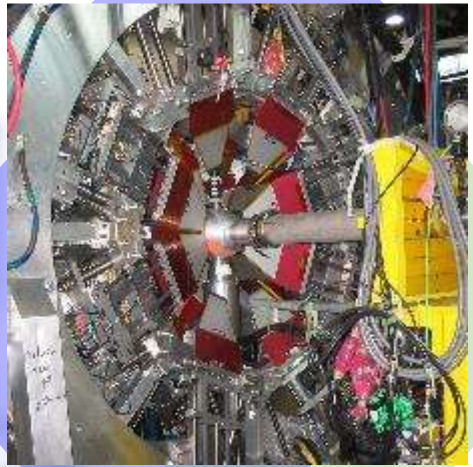


P.E. Garrett
D. Muecher, Th
C. Svensson
Guelph/TRIUMF



C. Andreoiu
K. Starosta
SFU
G.F. Grinyer
Regina



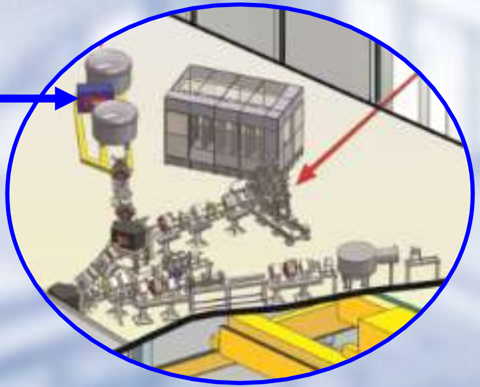


TIGRESS
In-flight γ-ray spectroscopy
+ ancillary detectors/tech.

BAMBINO
DESCANT
DSL
SHARC
SPICE
TIP
TRIFIC

High-energy experiments focus on reactions & excited states.

EMMA
Mass analyzer
for reactions



SAINT MARY'S UNIVERSITY
UBC
SFU
UNIVERSITY of GUELPH
University of Victoria

B. Davids
I. Dillmann

A.B. Garnsworthy
G. Hackman
R. Kruecken

C. Andreoiu
K. Starosta
SFU/TRIUMF

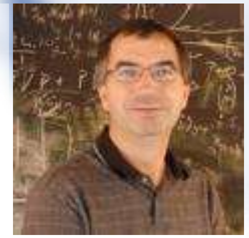
G. Christian
R. Kanungo
St. Mary's/TRIUMF
D. Muecher
Guelph/TRIUMF

High-energy experiments focus on reactions & excited states.

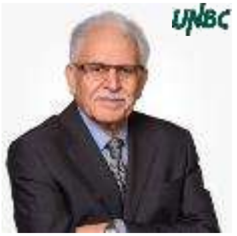
B. Davids

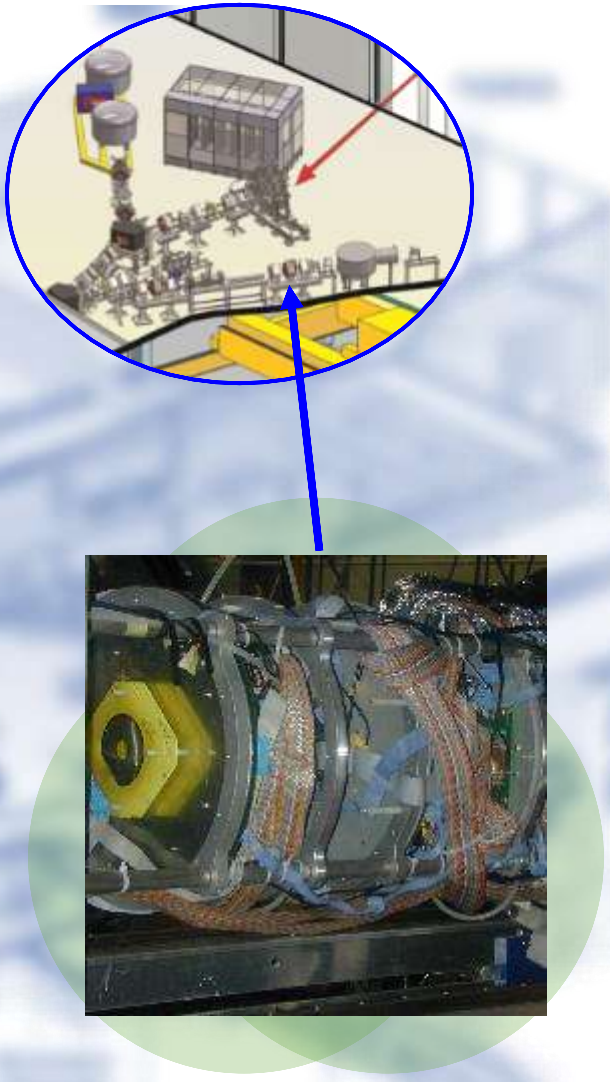
I. Dillmann
D. Hutcheon

P. Navrátil
C. Ruiz



A. Chen
McMaster
.
A. Hussein
UNBC





TUDA
Scattering array
Direct reactions

Medium-energy RIB experiments are tuned for astrophysically important reactions (0.15-1.8 A MeV).

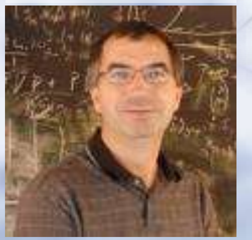
EMMA
TIGRESS

DRAGON
Gas target
Recoil spectrometer

B. Davids

I. Dillmann

P. Navrátil

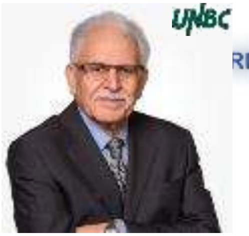


D. Hutcheon

C. Ruiz

A. Chen
McMaster

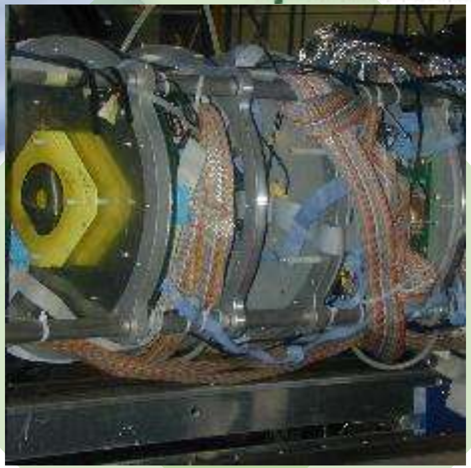
A. Hussein
UNBC



G. Christian
St. Mary's

High Resolution
Mass Separator
Target Stations
500 MeV
Protons
Cyclotron

TUDA
Charged-particle
reactions



Low-energy RIB experiments access ground-state properties.

I. Dillmann
A. Garnsworthy
G. Hackman
R. Kruecken

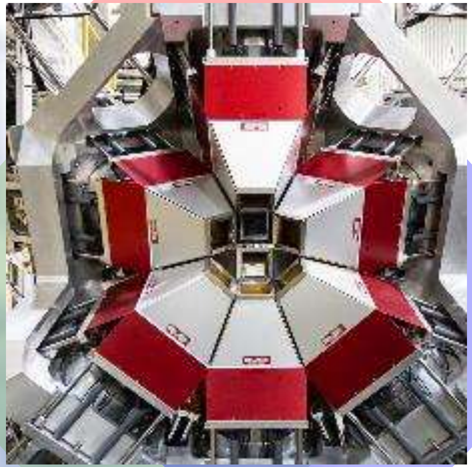



G. Ball

G.F. Grinyer
Regina


C. Andreoiu
SFU/TRIUMF

K. Starosta
SFU



GRIFFIN
Decay spectroscopy
+ ancillary detectors

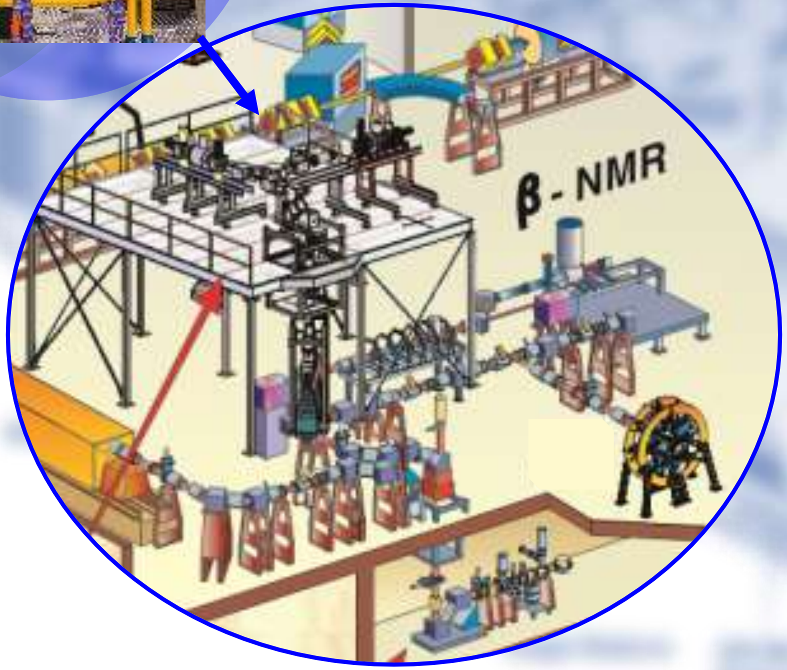
DESCANT
GPS
RCMP
ARIES

P.E. Garrett
D. Muecher
C. Svesson
Guelph/TRIUMF



Low-energy RIB experiments access ground-state properties.

TITAN
Masses & Q-values
In-trap γ-ray spec.



SFU
UNIVERSITY OF CALGARY
UNIVERSITY OF MANITOBA
INNOVATION.CA
McGill
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
University of Victoria
UNIVERSITY OF NOTRE DAME
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG
COLORADO SCHOOL OF MINES
UBC

J. Dilling
I. Dillmann
A. Kwiatkowski

C. Andreoiu
SFU/TRIUMF

T. Brunner
McGill/TRIUMF

R. Thompson
M. Wieser
Calgary

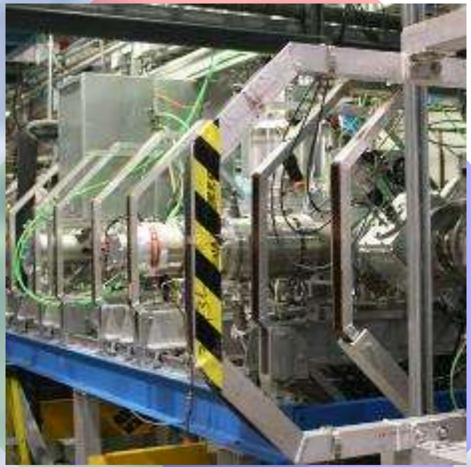
G. Gwinner
Manitoba

Low-energy RIB experiments access ground-state properties.

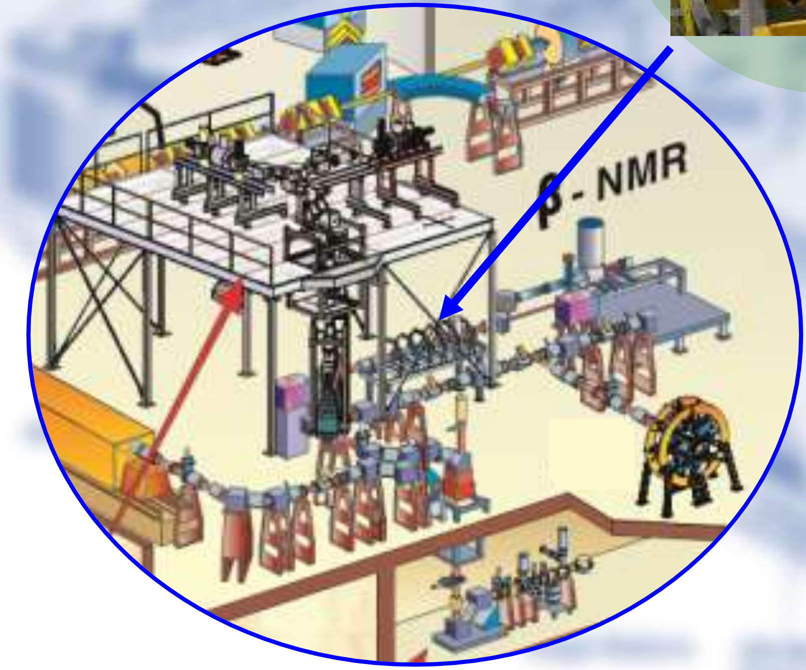
M.R. Pearson

F. Buchinger
McGill

J. Crawford
McGill



Laser Spectroscopy
Isotopic shifts



McGill
Université de Montréal
Tennessee Tech
Michigan State University
University of Liverpool
Manchester 1824
The University of Manchester
The University of Jordan

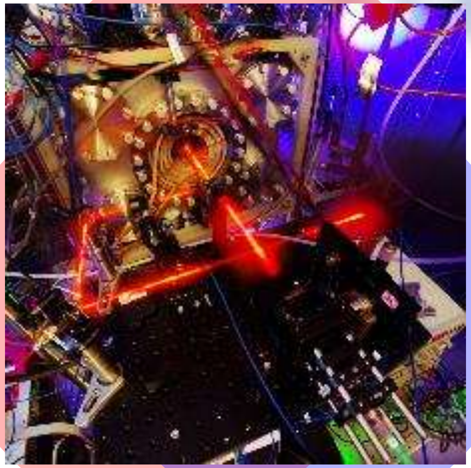
Low-energy RIB experiments access ground-state properties.

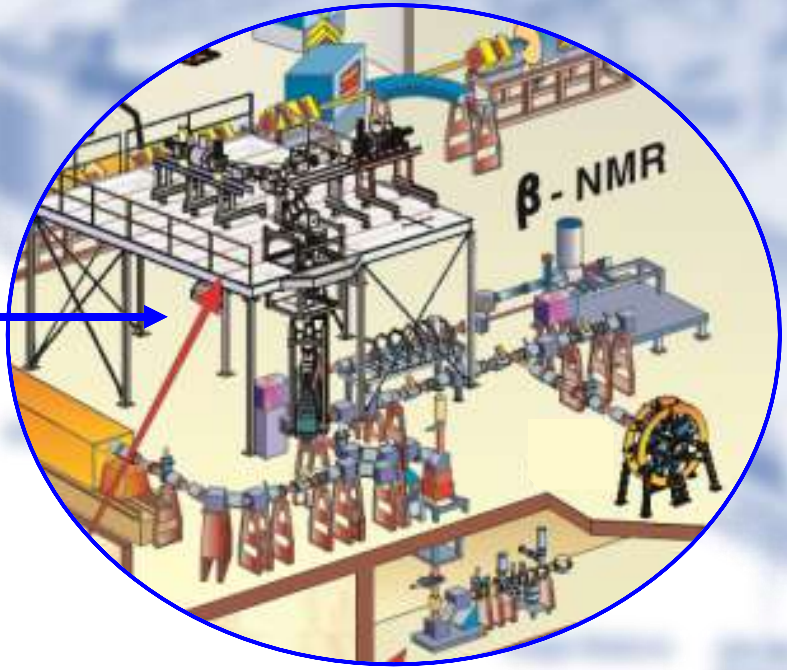
Nuclear Astrophysics
Fundamental Interactions
Nuclear Structure & Dynamics


J.A. Behr
M.R. Pearson


G. Gwinner
K. Sharma
Manitoba

Francium
Isotopic shifts
PNC hunt





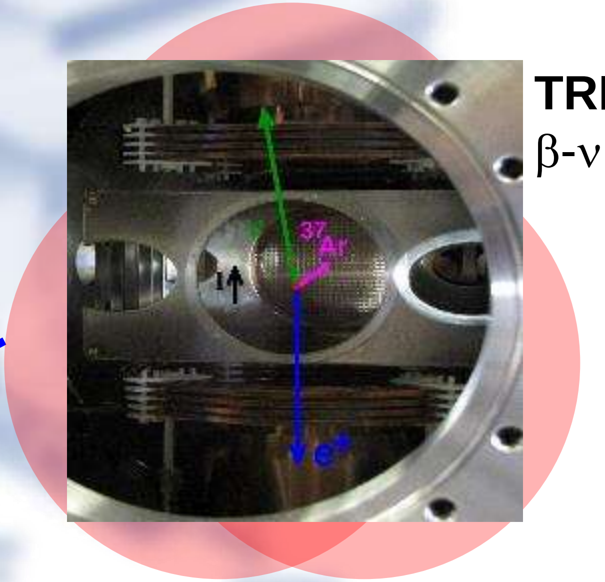
Low-energy RIB experiments access ground-state properties.


J.A. Behr
M.R. Pearson

G. Gwinner
Manitoba

University of Manitoba

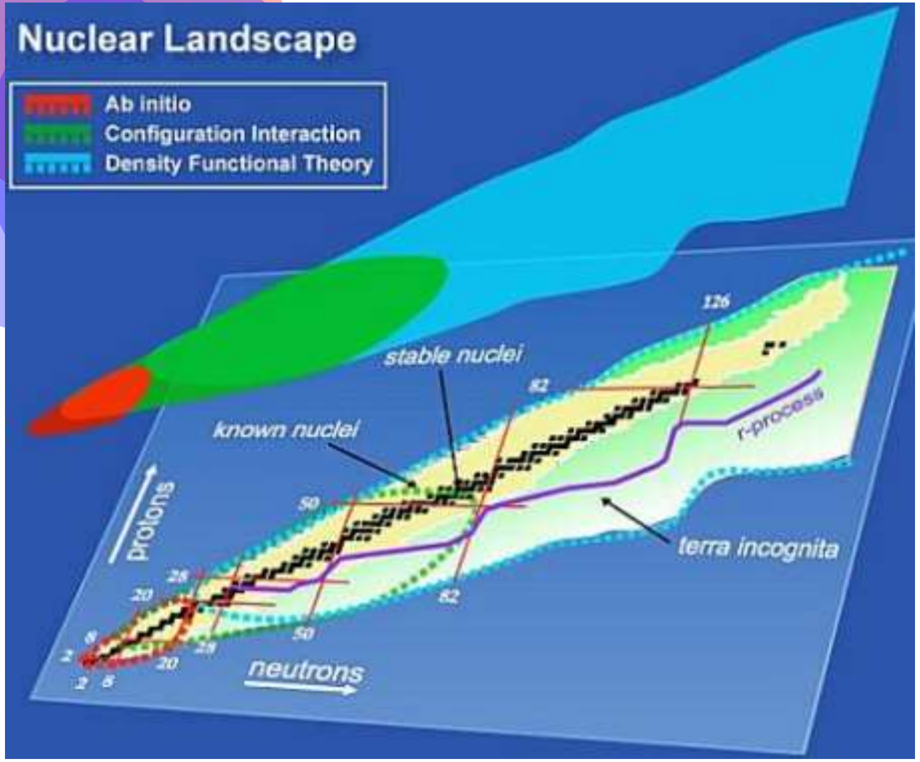
Tel Aviv University



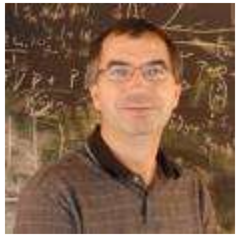
TRINAT
β-ν correlations

Strong collaboration with in-house theorists

Theory
ab-initio, χEFT, shell model



P. Navrátil



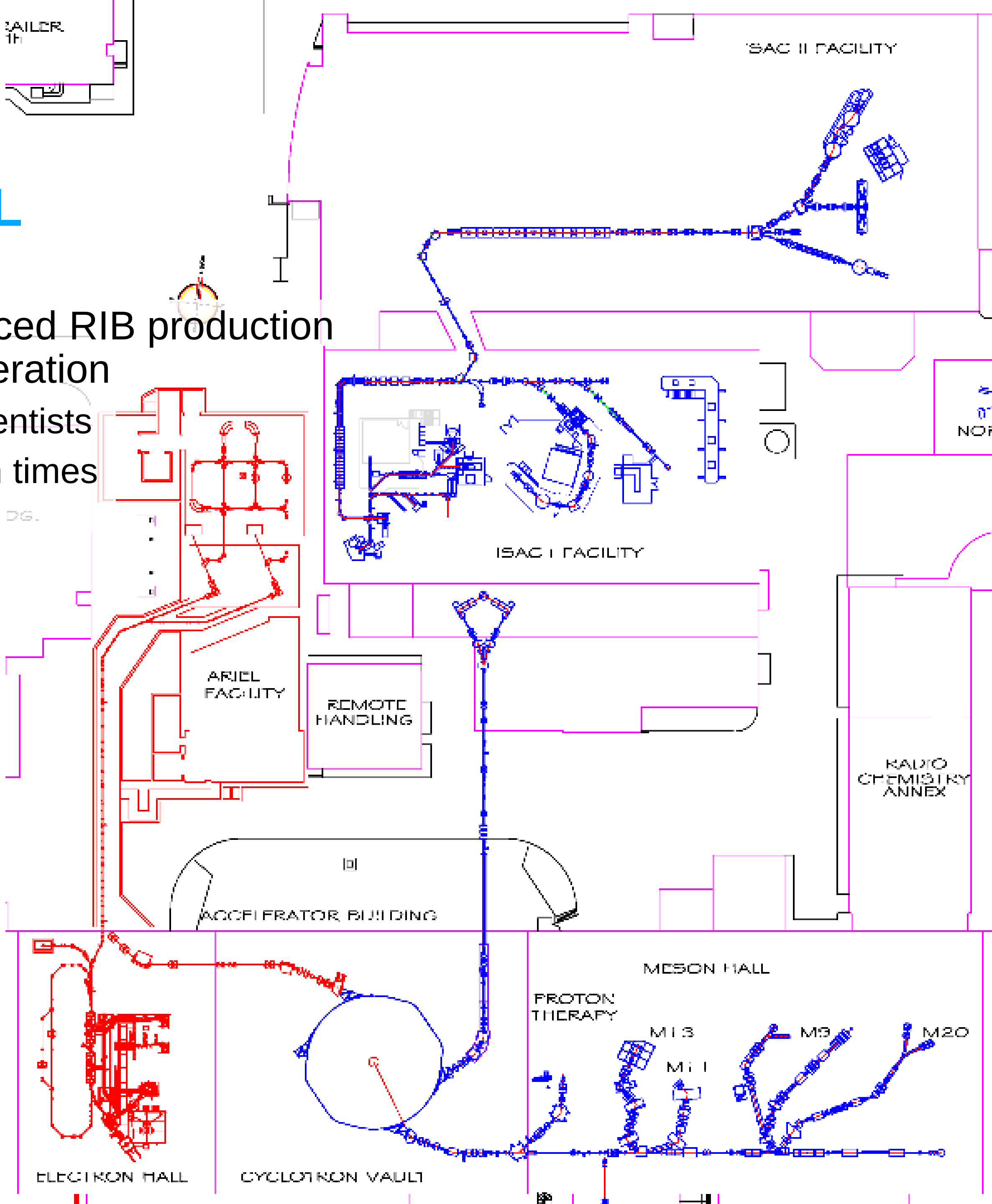
→ J.D. Holt, Th

D.E. Morrisssey

D. McKeen

ISAC experimentalists prepare for ARIEL

- ARIEL combines high-power proton- and electron-induced RIB production from 3 independent targets to enable full multi-user operation
    - Increases high-impact science, publications, & junior scientists
    - More beam development, higher purity, and longer beam times
    - Complementary to fast-beam facilities
- Nuclear structure and dynamics
    - unified theory for all nuclei
    - halo & dripline nuclei
    - shell evolution & 3N forces
- Nuclear astrophysics
    - H & He burning
    - neutron-rich nuclei along r-process path
- Precision tests of the fundamental interactions
    - Francium EDM & PNC experiments
    - TRINAT β-asymmetry experiment
    - unitarity of quark-mixing matrix



ARIEL's multi-user capabilities will empower experiments in nucl. structure, nucl. astrophysics, & fundamental symmetries.

proton spallation yields in uranium target

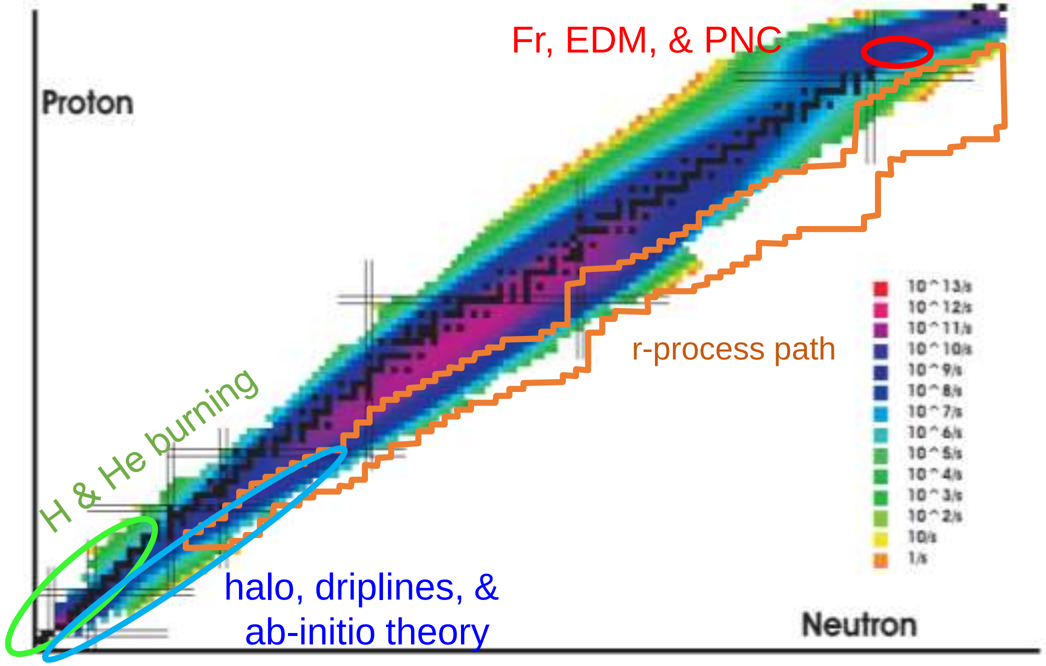
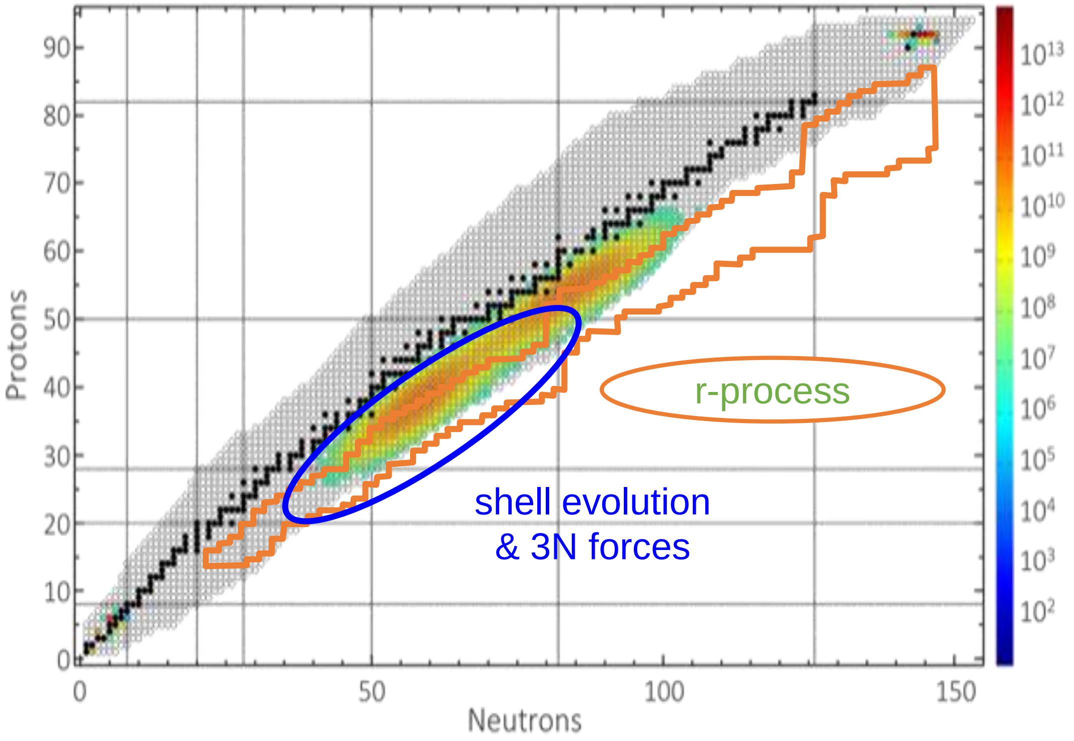
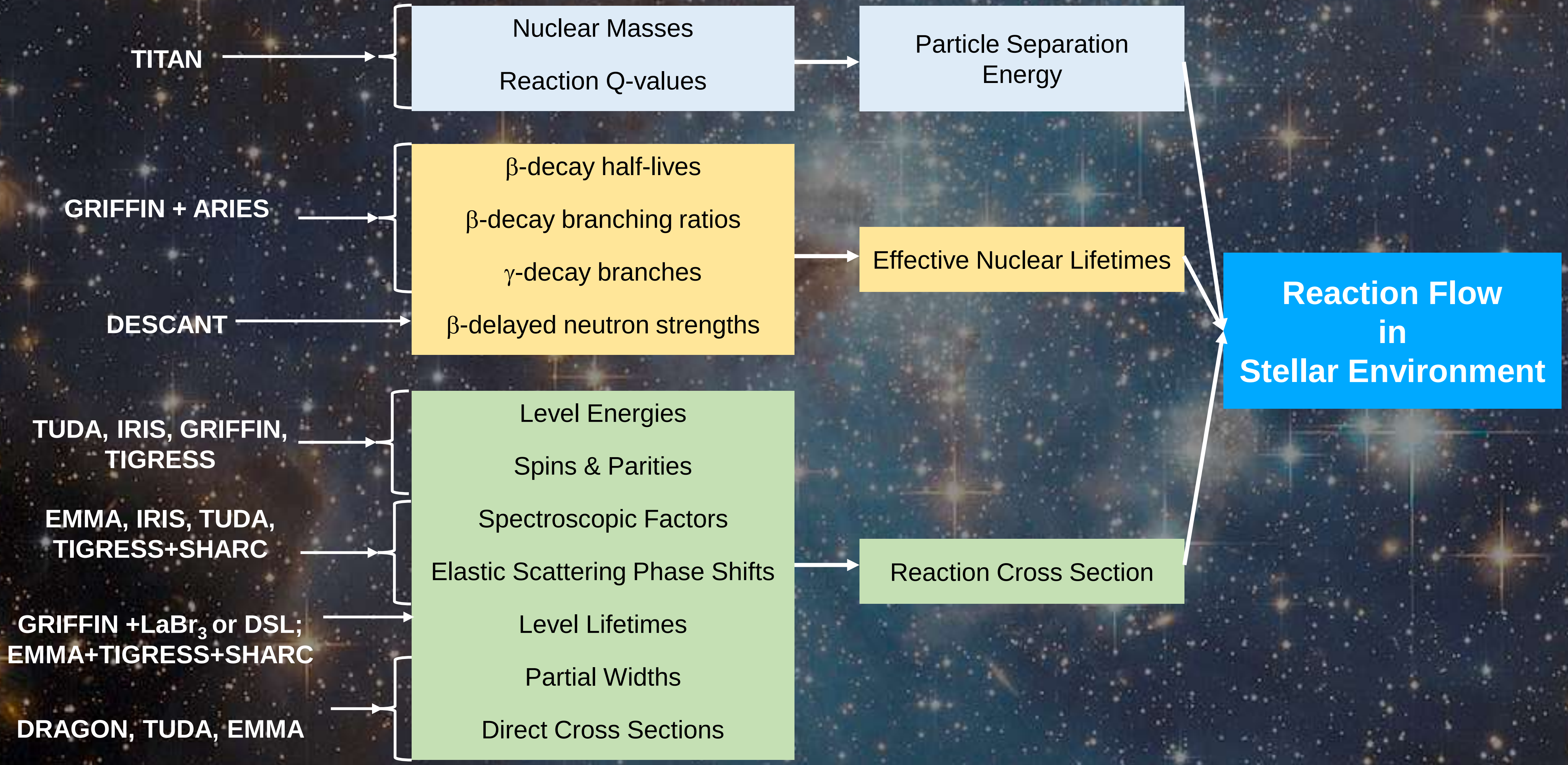


photo-fission yields in uranium target



→ A. Gottberg, Th

TRIUMF's nuclear astrophysics program in the era of multi-messenger astronomy



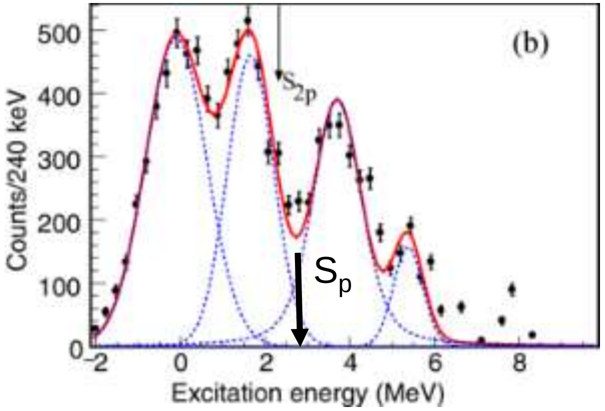
Nuclear Astrophysics
Nuclear Structure & Dynamics
Fundamental Interactions

Top Research Highlights

- 7s →8s transition of francium measured & compared to ab-initio theory, FrANPC, PRA 2018
- The proton dripline at the N=8 shell closure, IRIS + theory, PRC 2019
- Direct measurement $^{17}O(\alpha,\gamma)$ & impact on heavy nucleosynthesis, DRAGON, PLB 2019
- Shape coexistence in neutron-deficient Pb isotopes, GRIFFIN, PRC 2019
- 1st measurement of Gamow window of $^{76}Se(\alpha,\gamma)$ for γ-process, DRAGON, PLB 2020
- Masses of neutron-rich Ga and neutron-star merger calculations, TITAN, PRC 2020
- Development of time-reversal test in beta decay, TRINAT, DAMOP 2020 ← Franke, Mon
- L/K capture ratio of ^{7}Be directly measured, BeEST (Colorado School of Mines), PRL 2020 ← Leach, Th
- CoulEx of A=23 mirror pair & systematics of ab-initio *E2* strength, TIGRESS + theory, arxiv 2020
- β decay of ^{132}In and Spectroscopy of ^{132}Sn and ^{131}Sb, GRIFFIN, accepted in PRC
- Spectroscopy of ^{8}He and new N = 6 shell , IRIS + theory, submitted
- Magicity of neutron-rich Sc at N=34, TITAN + theory, submitted to PRL

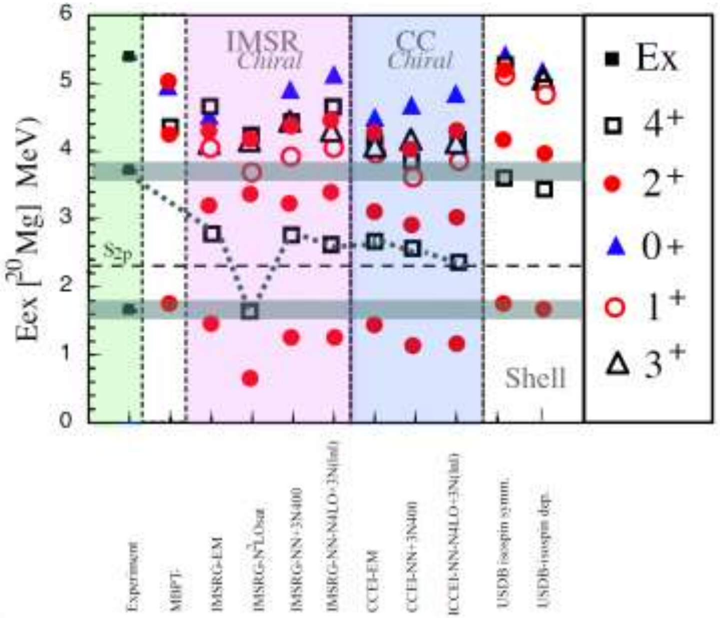
Reaction Spectroscopy @ IRIS

N = 8 shell @ proton drip-line (^{20}Mg)



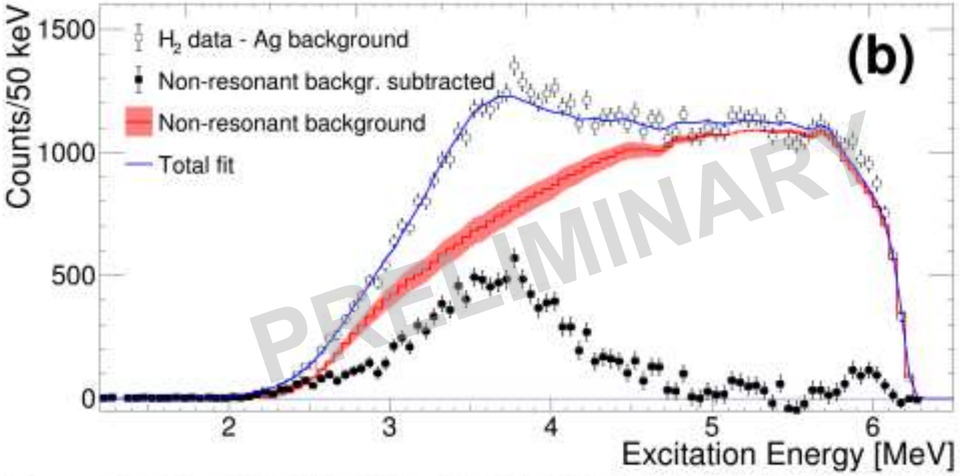
- First observation of resonance state
- Higher energy than predicted by chiral forces

J.S. Randhawa et al., PRC(Rapid) 2019



N = 6 shell @ neutron drip-line (^{8}He)

Deformation discovered in ^{8}He



M. Holl, R. Kanungo, et al. submitted to journal

Search for 0_2^+ state in ^{94}Kr

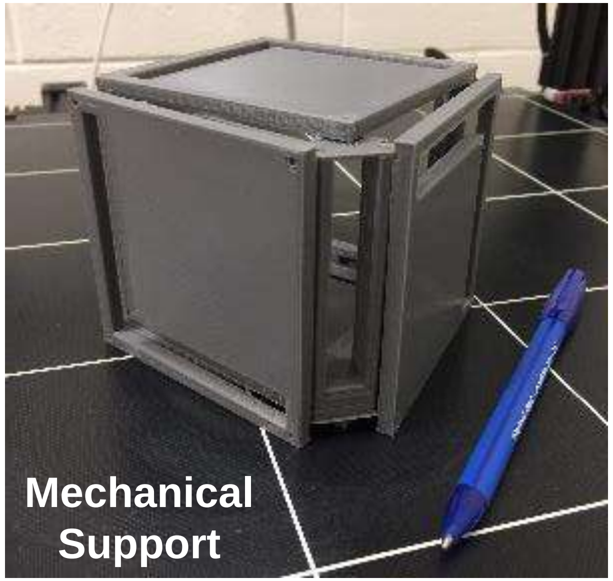
- ^{93}Kr(d,p) reaction first study
- only ~200 pps: pioneering accomplishment of low-energy reaction with such low-intensity radioactive ion beam

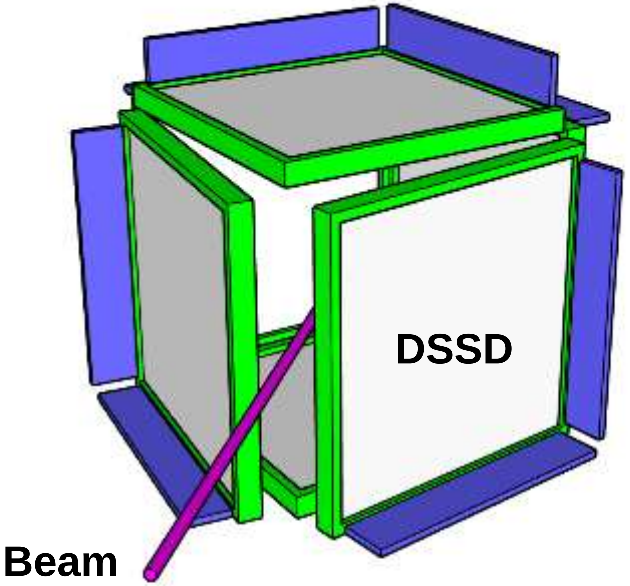
D. Walter, et al. *in preparation*

Slide courtesy of R. Kanungo, St. Mary's, Aug. 2020

Regina Cube for Multiple Particles (RCMP)

- New auxiliary detector for GRIFFIN
  - Charged particle detector
  - α decay and β delayed particles
  - Multiple particles (β2p, βαp, …)
  - Nuclear structure and astrophysics
- 6 DSSD detectors (micron BB7)
  - Active area: 64 x 64 mm^2
  - 6 x (32+32) strips = 384 channels
  - Thickness: 1mm (12 MeV protons)
  - Geometric efficiency ~80%
  - Fits inside GRIFFIN target chamber
- CFI JELF Project (Regina)
  - Gwen Grinyer (PI)
  - Total award: $130k
  - Anticipated completion: 2022





University of Regina

Faculty of Science

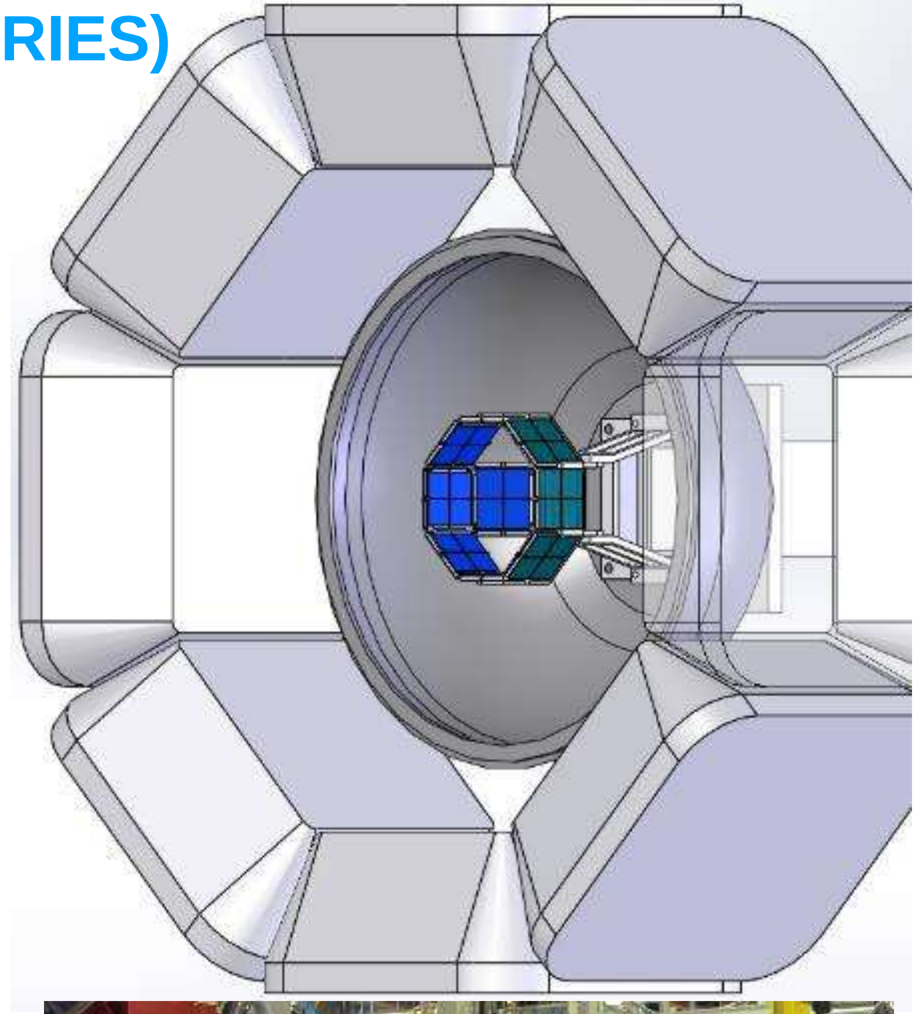
innovation SASKATCHEWAN

INNOVATION.CA

Slide courtesy of Gwen Grinyer, U. Regina, Aug. 2020

Ancillary detector for Rare Isotope Event Selection (ARIES)
A major upgrade of the SCEPTAR beta-tagging array for GRIFFIN

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



New ARIES beta-tagging array enables:

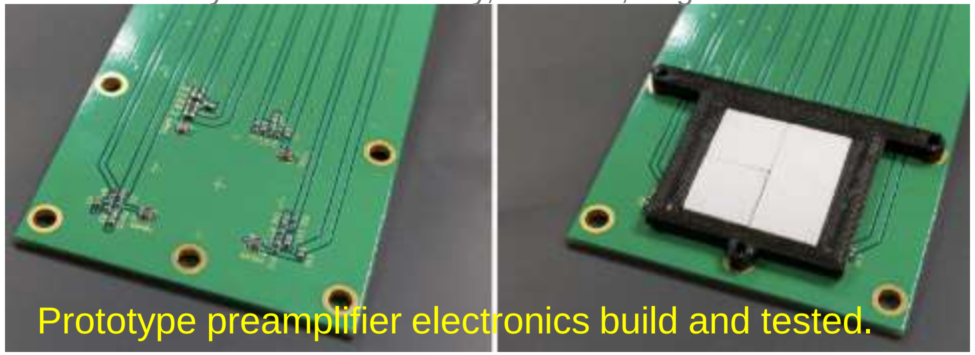
- Counting of high source activities ~20MBq with ~90% solid-angle coverage.
- Beta-gamma angular correlations with >50 unique angles.
- Beta-gamma fast coinc. timing (few ps) with $LaBr_3$(Ce) detectors (x2 eff. increase over ZDS).
- Easy and economical replacement of detectors contaminated with long-lived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

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

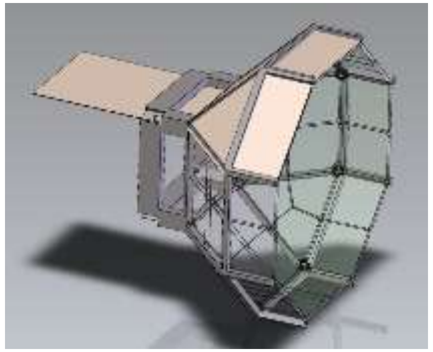
- 1.5mm thick BC422Q ultra-fast plastic scintillator.
- Laser-etching to optically-segment scintillators and prevent light loss.
- Light read-out using SiPM sensors printed on flexible circuit board ~50μm thickness and held in place with a 3D-printed support structure will provide energy and fast-timing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

First experiments anticipated in 2022

Slide courtesy of A. Garnsworthy, TRIUMF, Aug. 2020



Prototype preamplifier electronics build and tested.



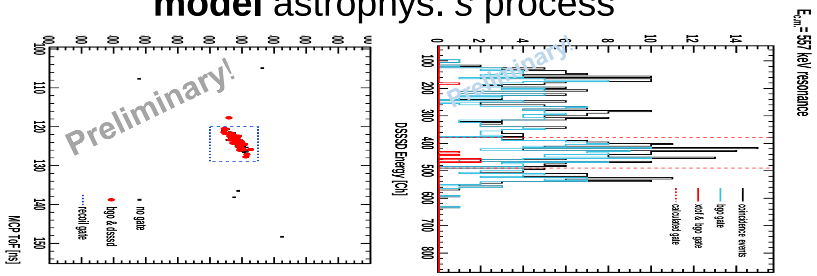
First chamber test achieved $<8x10^{-7}$ Torr.

DRAGON: from Big Bang Nucleosynthesis to supernovae

$^{22}Ne(\alpha,\gamma)/(\alpha,n)$

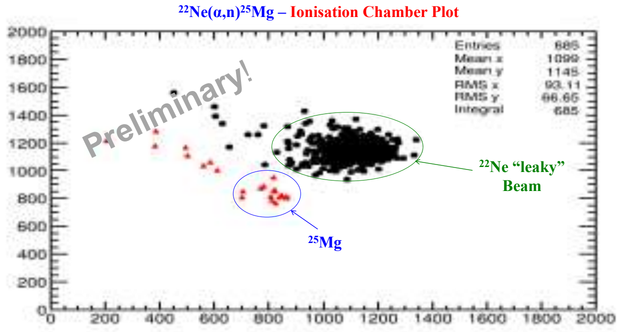
(collab. with Univ. of Surrey)

$^{22}Ne(\alpha,n)/^{22}Ne(\alpha,\gamma)$ needed to **accurately model** astrophys. *s* process



- Direct meas. in Gamow window for $^{22}Ne(\alpha,\gamma)$ (557 keV resonance)
- $\omega\gamma$(704keV) ~3x lower than literature

First direct (α,n) measurement with recoil separator!

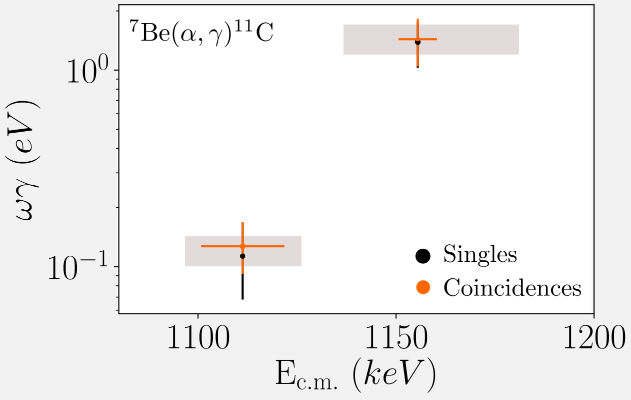


- (α,*n*) strength for E_x=11.32 MeV resonance is a **key uncertainty** in $^{22}Ne(\alpha,n)^{25}Mg$ rate at stellar temp.

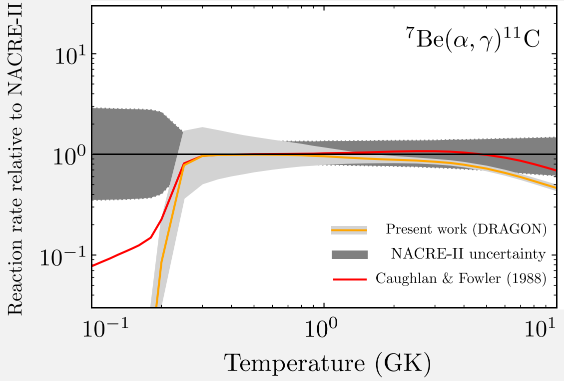
$^{7}Be(\alpha,\gamma)^{11}C$

(collab. with McMaster Univ.)

- Investigated effect on p-nuclei production in core-collapse SN
- First direct meas. of 2 resonance with previously unknown strengths



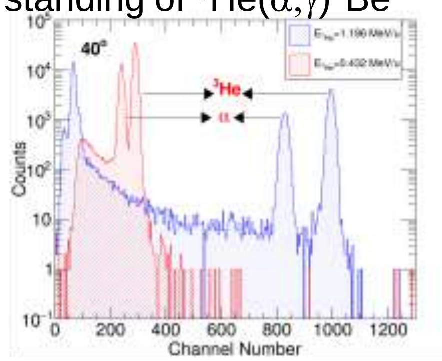
- Significantly reduced reaction rate uncertainty at νp-process temperatures!



$^{3}He+\alpha$ with SONIK

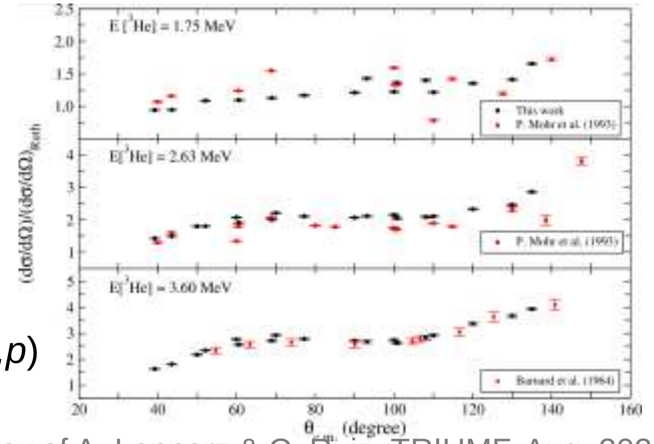
(collab. With Colorado School of Mines & Ohio Univ.)

- $^{3}He(\alpha,\gamma)^{7}Be$: Key reaction in BBN & solar ν physics
- Elastic scat. cross-sec. essential for theoretical & phenomenological understanding of $^{3}He(\alpha,\gamma)^{7}Be$



- 9 energies, including lowest energy at E_{cm} = 0.4 MeV thus far
- Improved precision & successfully characterized apparatus

Up next:
$^{7}Be(\alpha,\alpha)$ & $^{7}Be(p,p)$



Slide courtesy of A. Lennarz & C. Ruiz, TRIUMF, Aug. 2020

DRAGON & TUDA: from this 5YP into the ARIEL era

- **DRAGON** → unique versatility and sensitivity… currently the only fully-operating astrophysical recoil separator at a RIB facility
- Currently, either:
  1. -*Pioneering* measurements. i.e. low-signal, large-uncertainty measurement of reaction hitherto inaccessible (weak RIBs, low energy stable beam) or
  2. -*Precision* measurements, i.e. high intensity stable beam, smaller more controlled systematics than normal kinematics
- (1) is considered 'incomplete' reaction study → future study needed
- Limitation is ***beam-time competition*** (1-2 weeks RIB per year.. Only enough time to measure one (dominant) resonance)
- ARIEL 3x beam will make possible RIB experiments of several weeks:

  → complete, comprehensive measurements of (p,γ) (α,γ) reactions with reduced systematics

  → highly competitive with underground facilities, almost matching luminosity with high-intensity SIB + superior background rejection

Near future: (5YP)

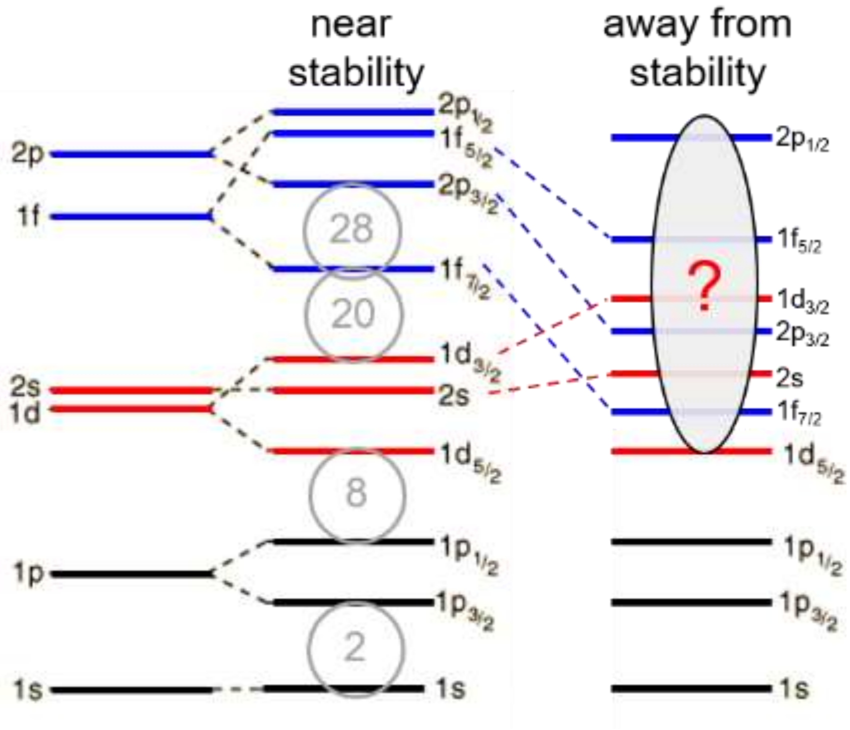
- Addition of $LaBr_3$ array to improve DRAGON sensitivity 10-fold (determine resonance energy, required precisiod, 10x less statistics)

  → Also used as ancillary detectors in TUDA and EMMA → G. Christian, Th for other astro ancillary detectors
- Usage of GRIFFIN HPGe clovers @DRAGON enable low-energy measurements disentangling nuclear structure effects, e.g. *proton halo subthreshold states*
- Beam time arguments also apply to TUDA, SONIK facility, where experiments are limited simply by integrated beam on target → enhanced reach, sensitivity
- Note: CANREB promising to enable massive beams to DRAGON, e.g. $^{35,37}Ar$ → Opens up *rp*-process studies

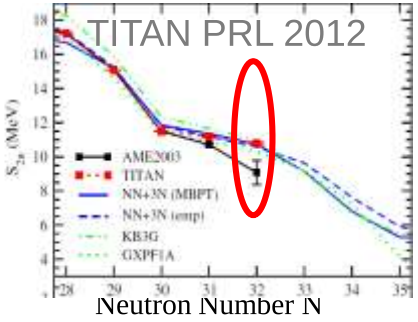
Slide courtesy of A. Lennarz & C. Ruiz, TRIUMF, Aug. 2020

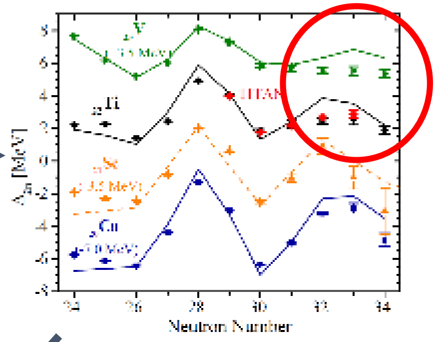
Emergence & quenching of N=32,34 shells shells via TITAN mass spectrometry of Ca, Sc, Ti, and V.

Nucleons occupy stable configurations (shells)



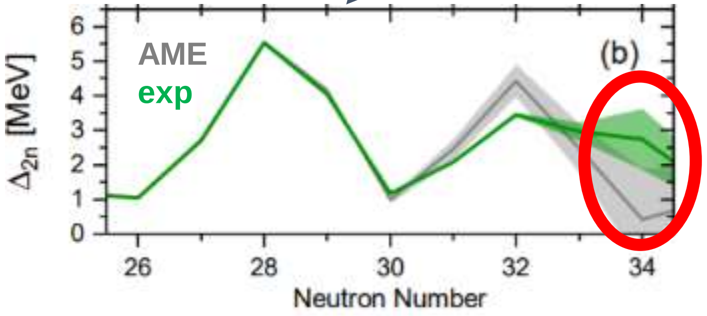
which may evolve as Z/N grows unstable.

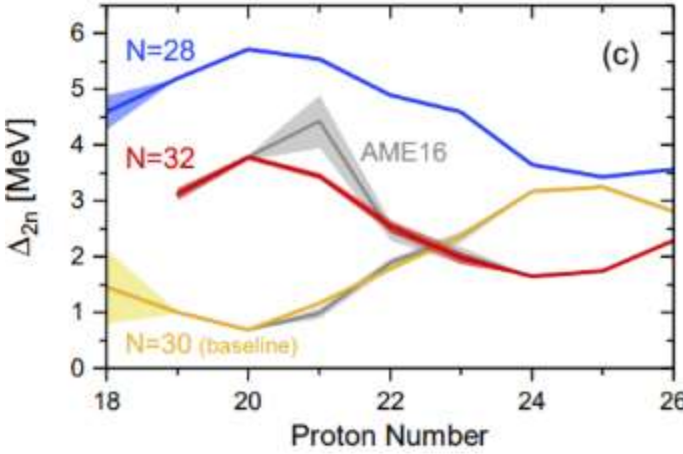




TITAN + Theory
PRL 2018

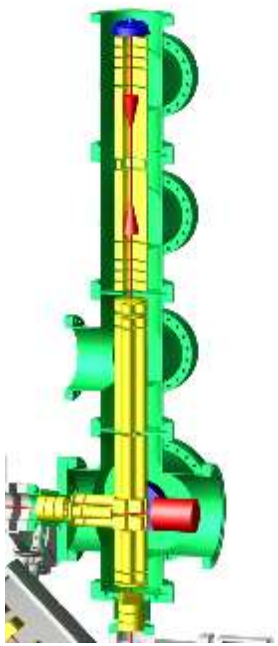
TITAN + Theory
+ LEBIT
submitted PRL





N=34 in V,
E. Dunling, *et al.*
in preparation

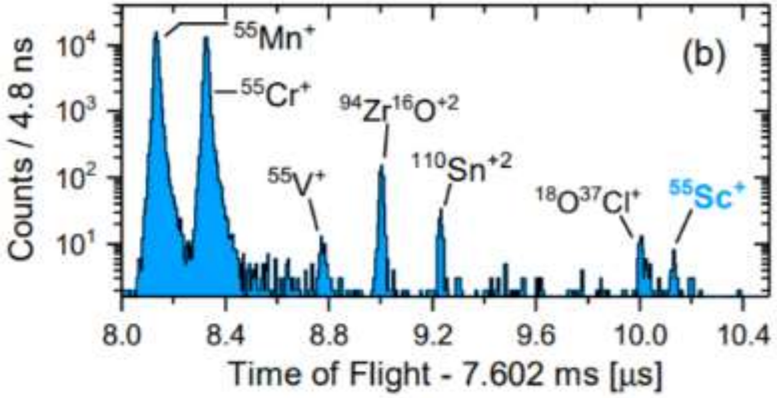
TITAN mass-spectrometry upgrades are focused on sensitivity and precision.



JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

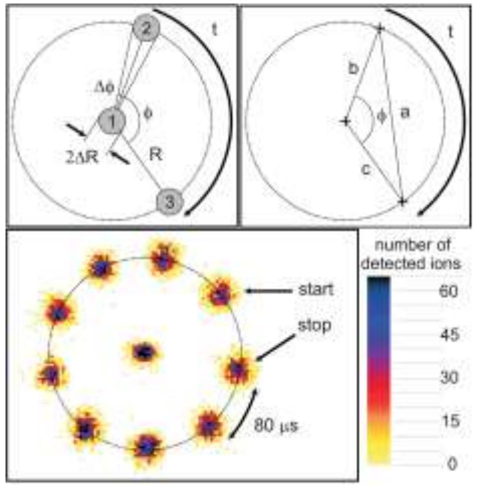
Multi-Reflection Time-Of-Flight Mass Separator

- Non-scanning → sensitivity
- Broadband → more measurements/time
- MRS & "re-trapping" technique → better purification
- δm/m ~10^{-7}, ioi/cont. ~1:10^5, sensitivity <0.01 pps



Measurement Penning trap

- Implementing new phase-imaging ion-cyclotron-resonance technique → precision, resolving power, sensitivity
- Cryogenic upgrade for longer measurement times at high charge states for both techniques → precision, resolving power
- Present: δm/m ~10^{-9}, ioi/cont. ~1:10^3, sens. ~10



MR-TOF: S. Beck, et al., in preparation; A. Jacobs, MSc, UBC 2020; E. Dunling, PhD work; MR-TOF spectrum: E. Leistenschneider, submitted to PRL;
MPET: E. Leistenschneider, PhD, UBC 2019; M. Lykiardopoulou, PhD work; PI-ICR image: S. Eliseev, *et al.* PRL 110 (2013) 082501

Nuclear physics at ISAC is at the forefront.

- State-of-the-art experimental facilities investigate and, with ARIEL, will push the boundaries to study
  - Unified theory of nuclei, evolution of nuclear shells, 3N forces, etc.
    - Reactions along the proton and neutron driplines @ IRIS
    - Masses at N=32,34 @ TITAN
  - Nucleosynthesis from H burning to r-process, multi-messenger astronomy
    - Reactions to probe element production from Big Bang to core-collapse supernovae @ DRAGON
  - Precision tests for physics beyond the Standard Model → Franke, Mon

- Breakthroughs are facilitated through continued interplay between cutting-edge experiments and theory.

Preparations for the ARIEL era are underway.

- Experimental upgrades are being completed or developed to achieve
  - Higher sensitivity
  - Higher-rate capabilities
  - Reduce systematics
  - Improved detection systems: EXACT-TPC @ IRIS, ARIES & RCMP @ GRIFFIN, PI-ICR @ TITAN, neutron det. @ TUDA & EMMA ← G. Christian, Th
  - Polarized beams ← Dunsinger, Wed

Nuclear-physics experiments need

- Reliable beam delivery
- Cleaner beams
- Higher efficiency re-accelerated beams

CANREB

- (More) beam development
- More shifts: longer runs or more frequent experiments

ARIEL

Thank you
Merci

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Discovery, accelerated