TRIUMF

Canada's National Laboratory for Particle and Nuclear Physics

Nuclear structure and astrophysics investigations at TRIUMF-ISAC

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Principal Scientist for ARIEL,
Research Scientist, TRIUMF

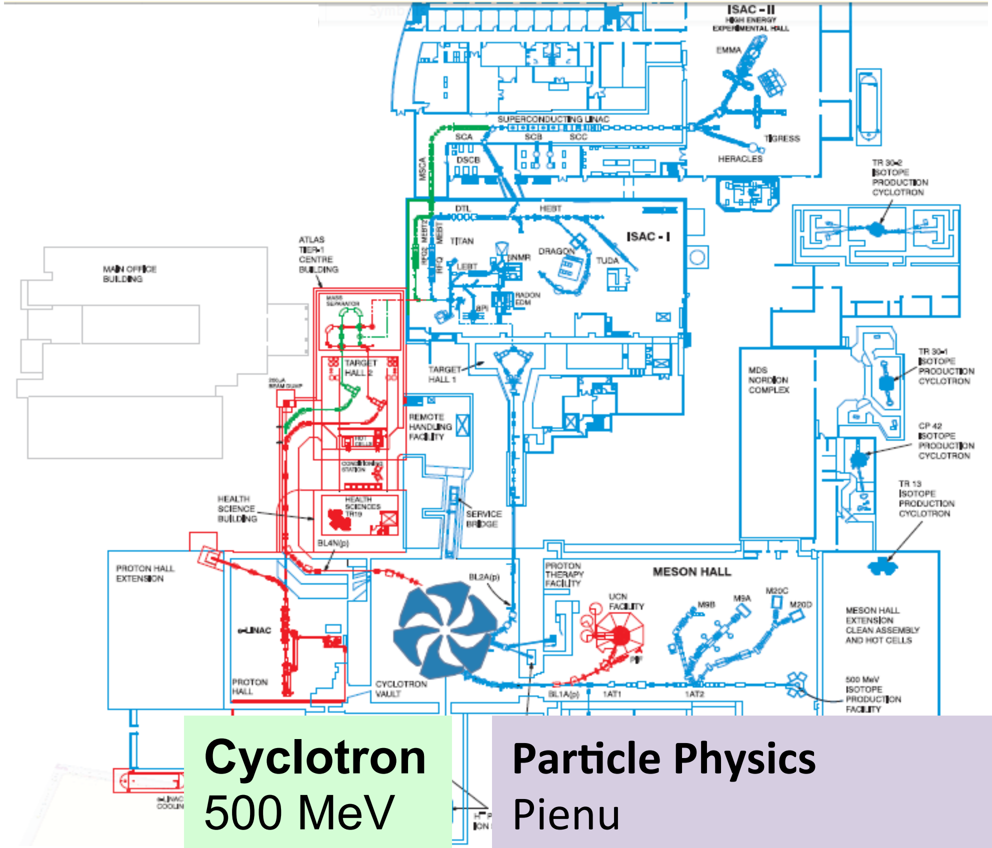
March 15th 2017

Nuclear Reactions: A Symbiosis between Experiment, Theory and Applications
INT Workshop, University of Washington, Seattle

TRIUMF: Canada's National Laboratory

TRIUMF was founded in 1968 and has delivered nearly 50 years of accelerator-based science and innovation for Canada, and is engaging the World.

TRIUMF's accelerator complex



Nordion
commercial medical
isotope production
3 cyclotrons

Cyclotron
500 MeV
350 μA

Particle Physics
Pienu
Ultra Cold Neutrons

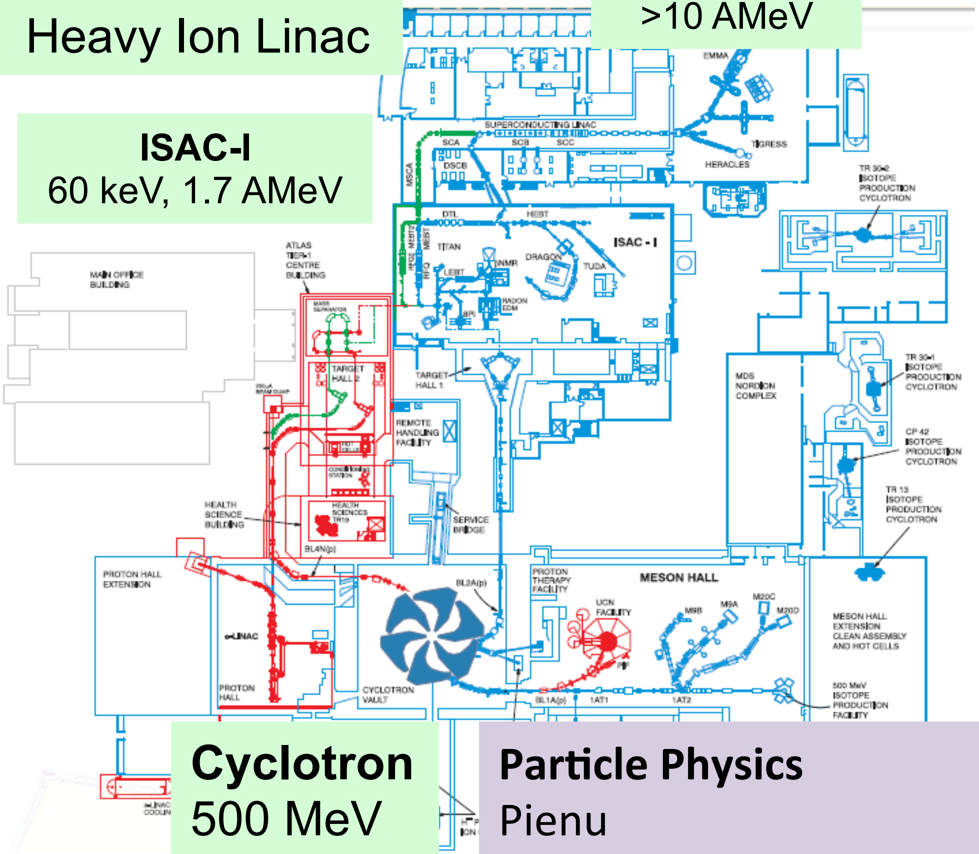
CMMS
Centre for Molecular and
Material Science (μSR)

TRIUMF’s accelerator complex

40 MV SRF Heavy Ion Linac

ISAC-II
>10 AMeV

ISAC-I
60 keV, 1.7 AMeV



ISAC (Isotope Separator and ACcelerator)

Rare Isotope Facility

- Nuclear Structure
- Nuclear Astrophysics
- Fund. Symmetries
- CMMS (βNMR)

Nordion

commercial medical isotope production

3 cyclotrons

Cyclotron

500 MeV

350 μA

Particle Physics

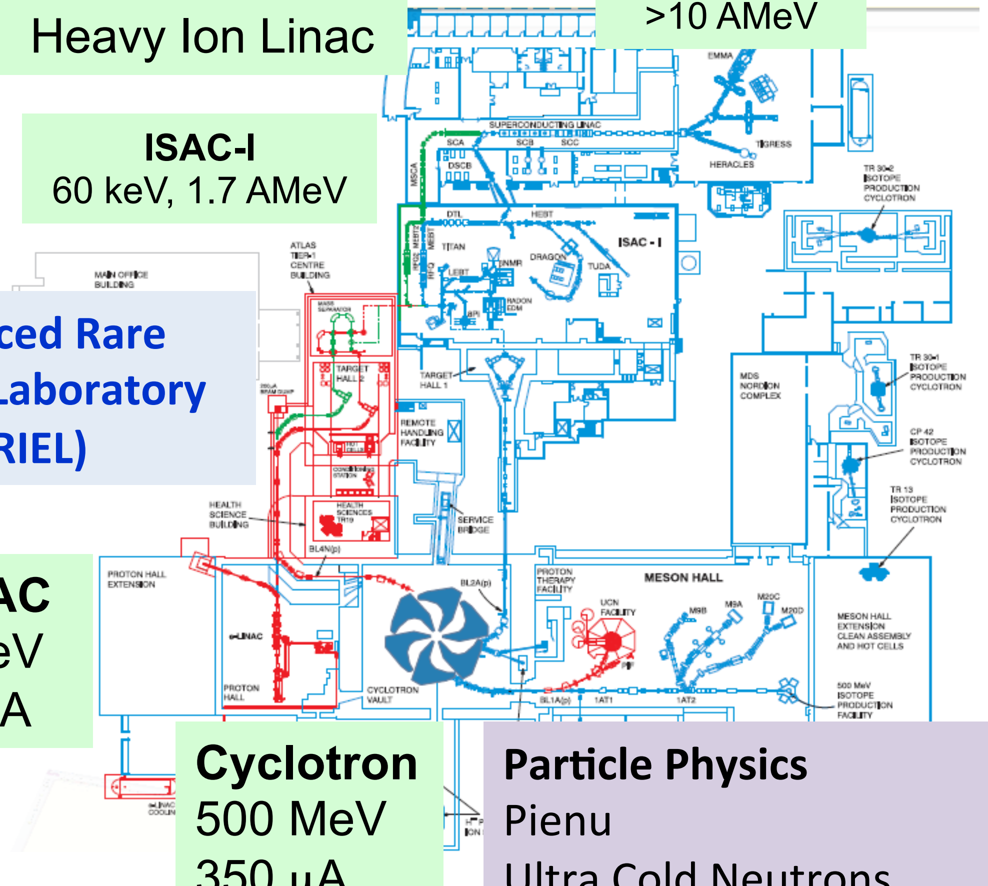
Pienu

Ultra Cold Neutrons

CMMS

Centre for Molecular and Material Science (μSR)

TRIUMF's accelerator complex



40 MV SRF
Heavy Ion Linac

ISAC-II
>10 AMeV

ISAC-I
60 keV, 1.7 AMeV

Advanced Rare Isotope Laboratory (ARIEL)

eLINAC
35 MeV
100 μA

Cyclotron
500 MeV
350 μA

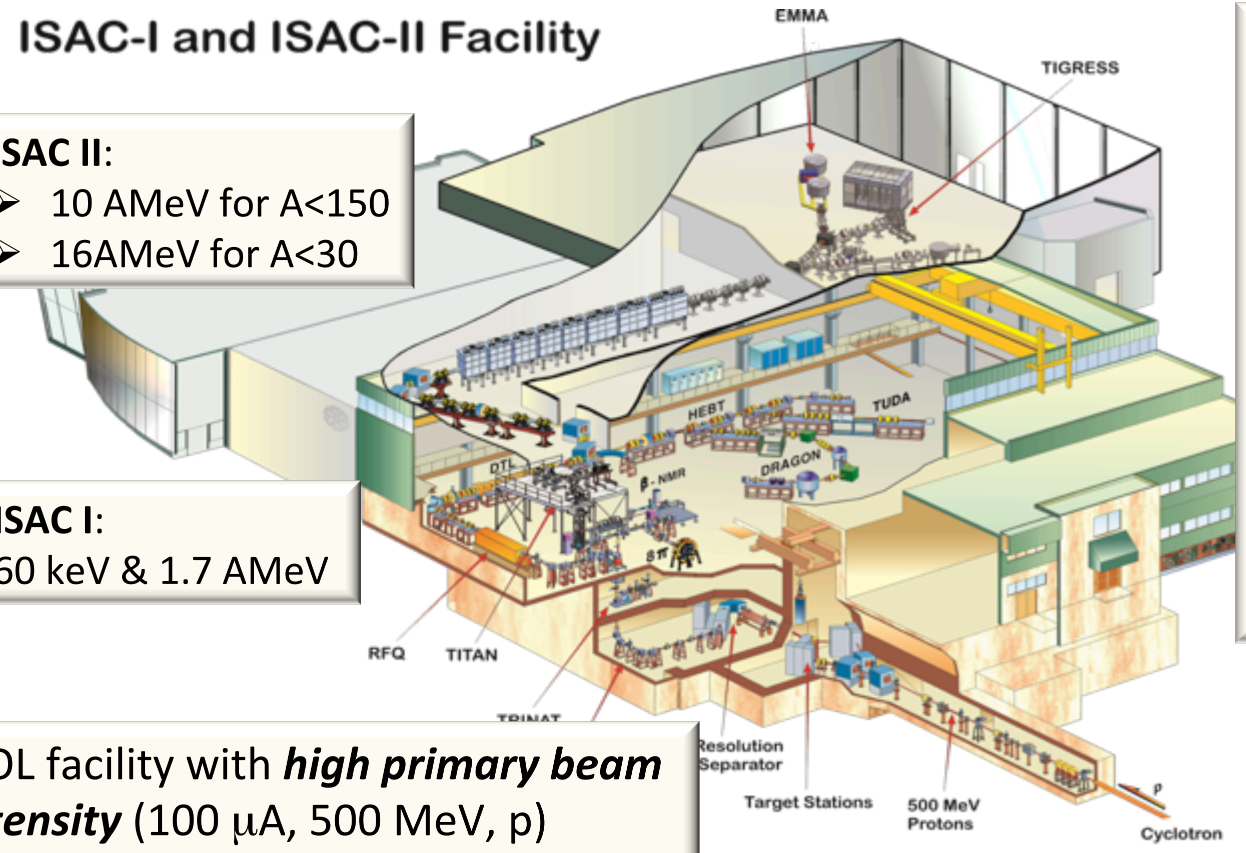
ISAC (Isotope Separator and ACcelerator)
Rare Isotope Facility
- Nuclear Structure
- Nuclear Astrophysics
- Fund. Symmetries
- CMMS (βNMR)

Nordion
commercial medical isotope production
3 cyclotrons

Particle Physics
Pienu
Ultra Cold Neutrons

CMMS
Centre for Molecular and Material Science (μSR)

ISAC rare isotope facility



ISAC II:

- ➢ 10 AMeV for A<150
- ➢ 16AMeV for A<30

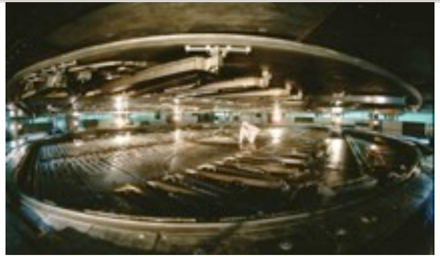
ISAC I:

60 keV & 1.7 AMeV

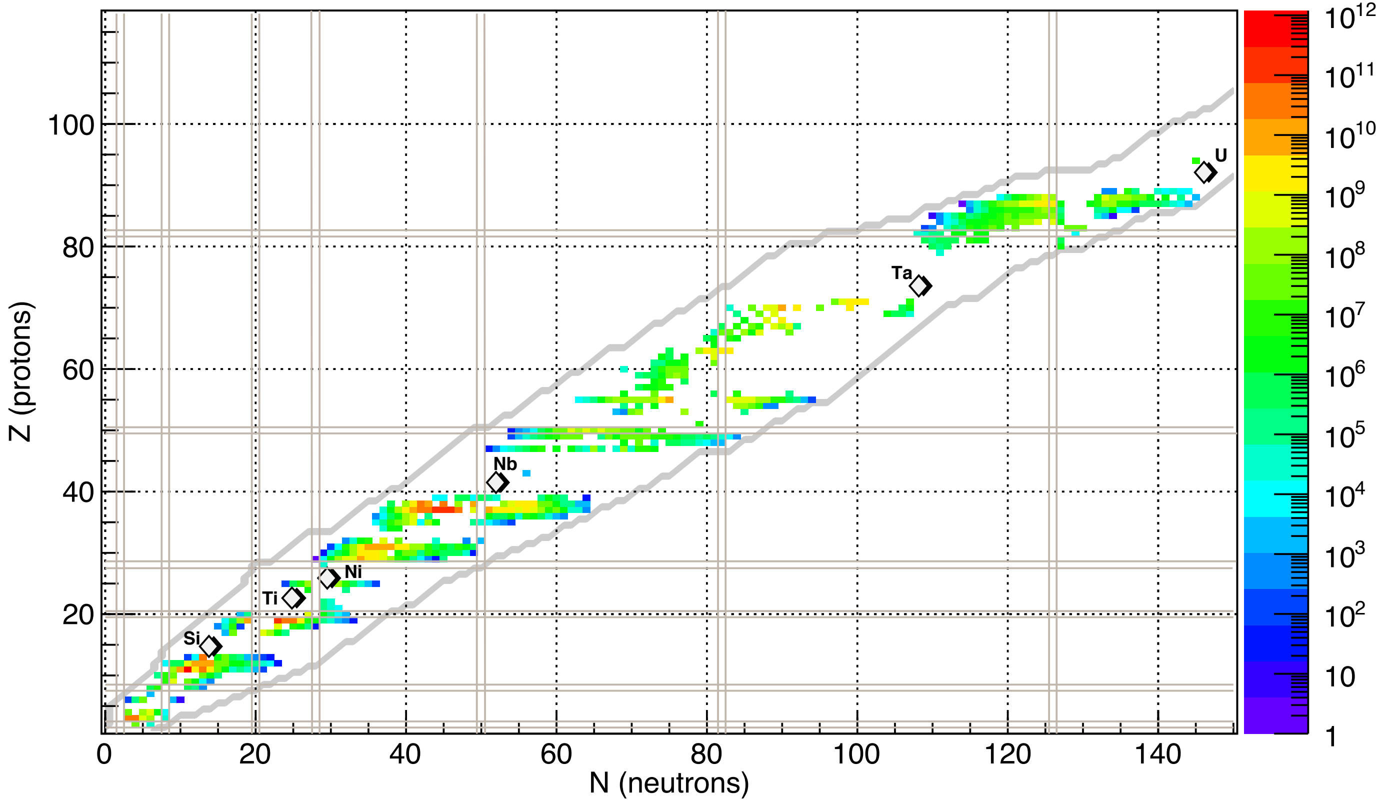
ISOL facility with ***high primary beam intensity*** (100 μA, 500 MeV, p)
Delivering RIBs since 1999.

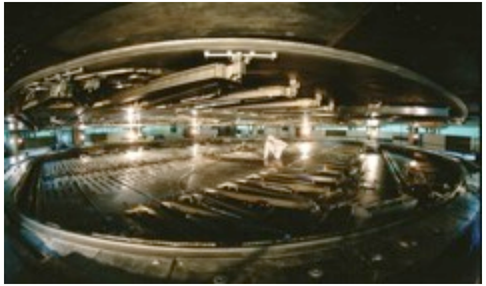
Programs in

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



Isotopes delivered at ISAC (Updated June 2016)



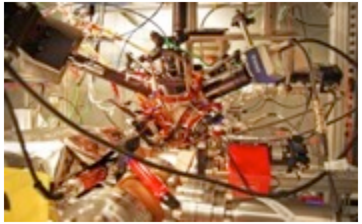


Target materials:
SiC, TiC, NiO, Nb, ZrC, Ta, U
Ion sources:
Surface, FEBIAD, IG-LIS

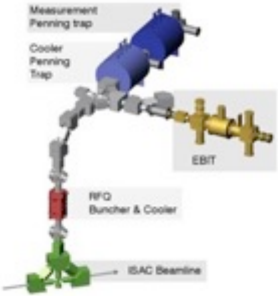
ISAC experimental areas

Low energy RIBs
< 60 keV

FRANCIUM MOT
(PNC, anapole moment)

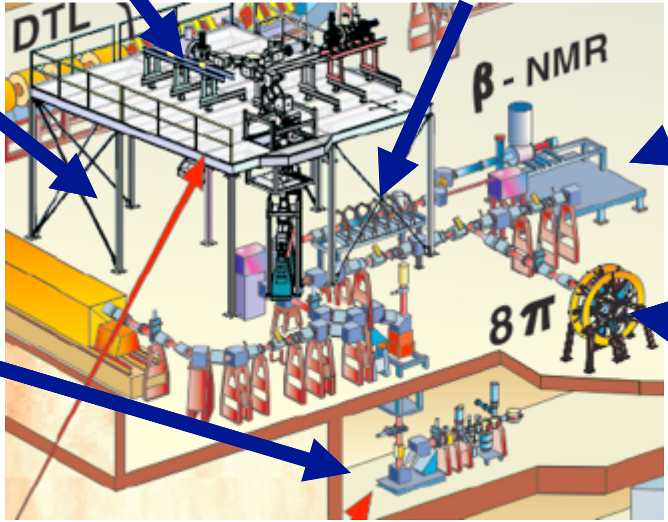


TRINAT
Neutral Atom Trap
(βν–neutrino correlations)



TITAN
Penning Traps
(masses,
in–trap decay)

Polarizer beamline
Laser spectroscopy, MTV
CPT test, betaNMR



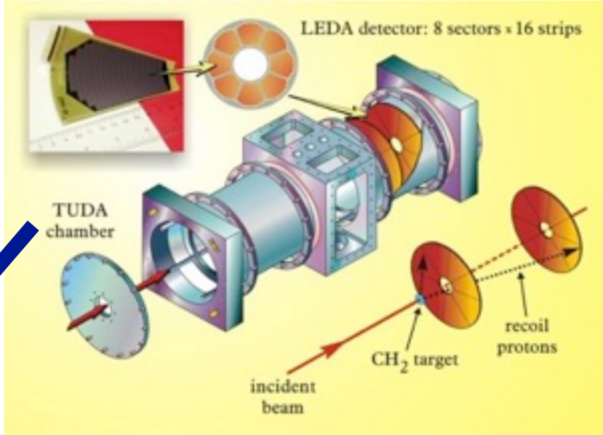
Beta–NMR
Material science

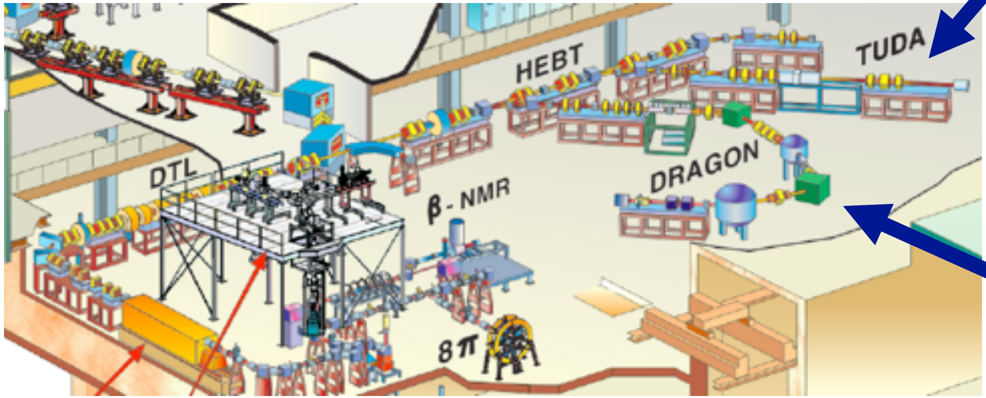
GRIFFIN
Gamma & Electron
spectrometer
(decay spectroscopy,
superallowed decays)

ISAC experimental areas

Medium energy RIBs
~ 0.15 -1.7 AMeV

TUDA
Astrophysical charged particle reactions



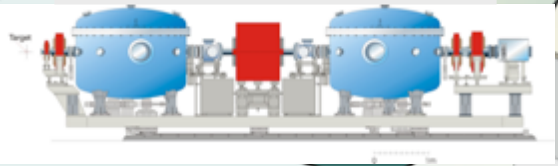


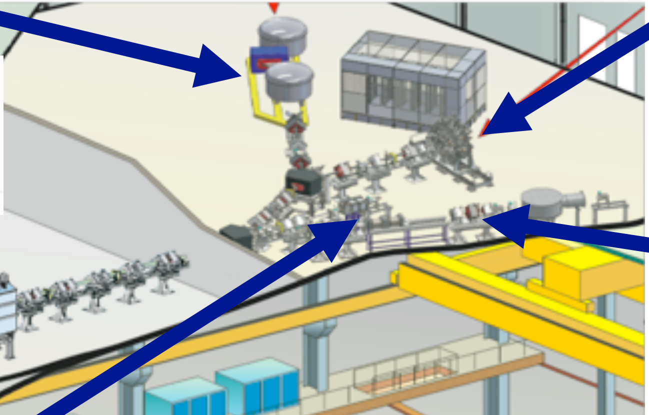
DRAGON
Astrophysical capture reactions

ISAC experimental areas

High-energy RIBs
> 6 AMeV

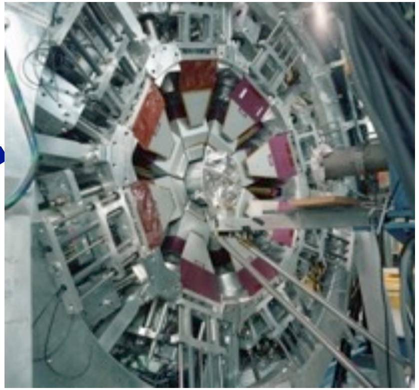
EMMA **(2017)**
Mass analyzer for nuclear reactions



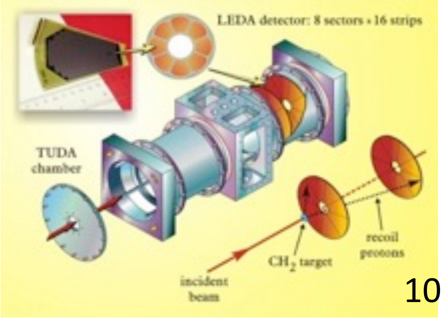


TIGRESS + **auxiliary detectors**

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

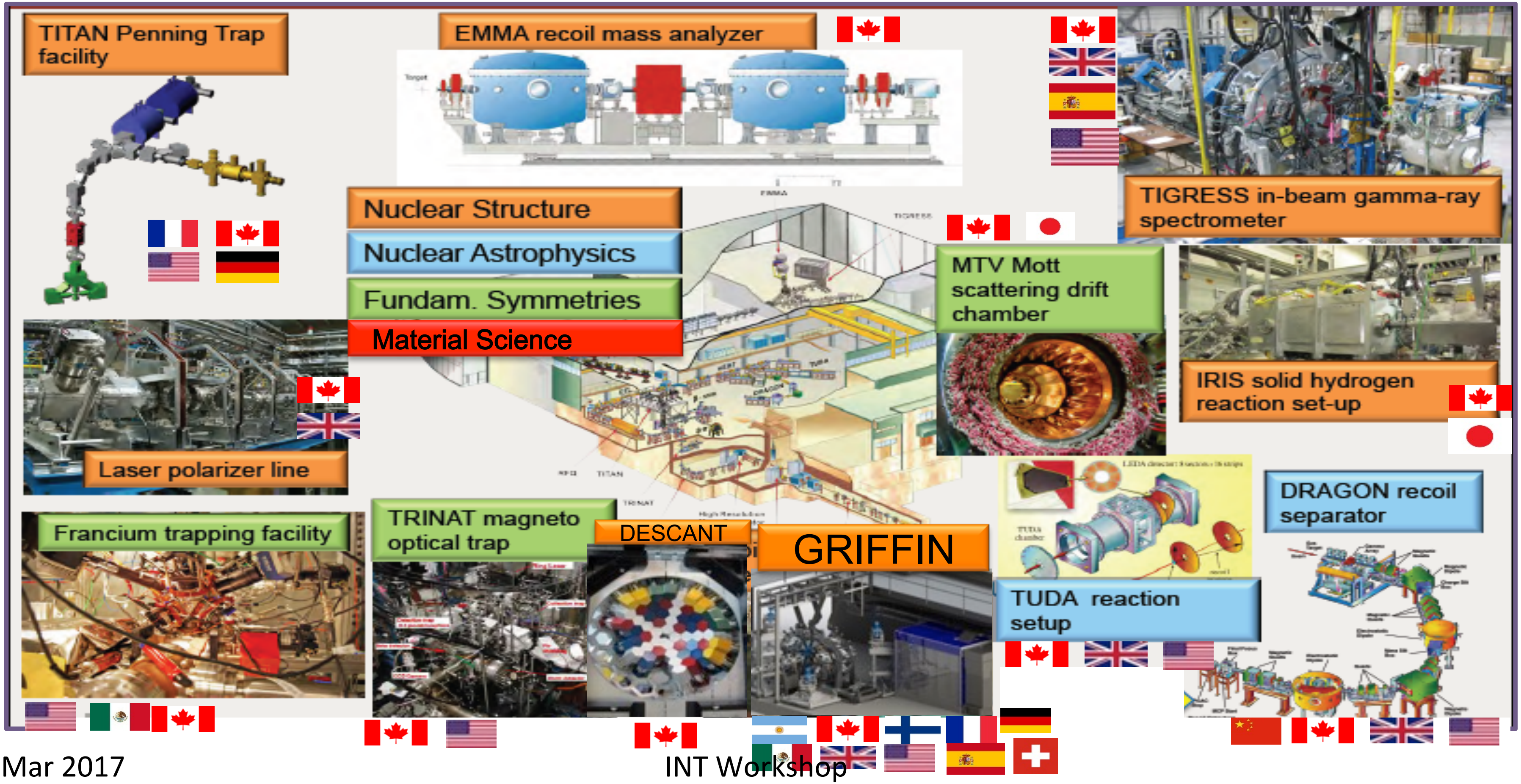


TUDA
Scattering array for direct reactions

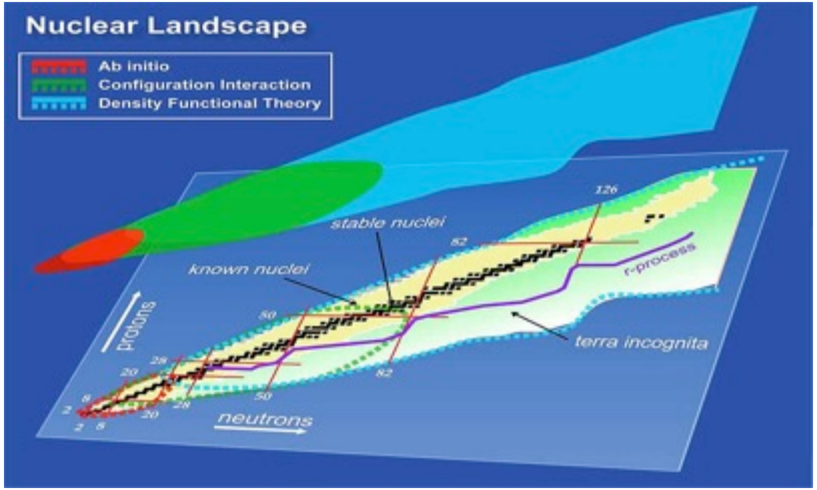


IRIS
Solid hydrogen target for direct nuclear reactions

Experimental facilities and programs of ISAC



Isotopes for developing and refining theory for nuclear physics



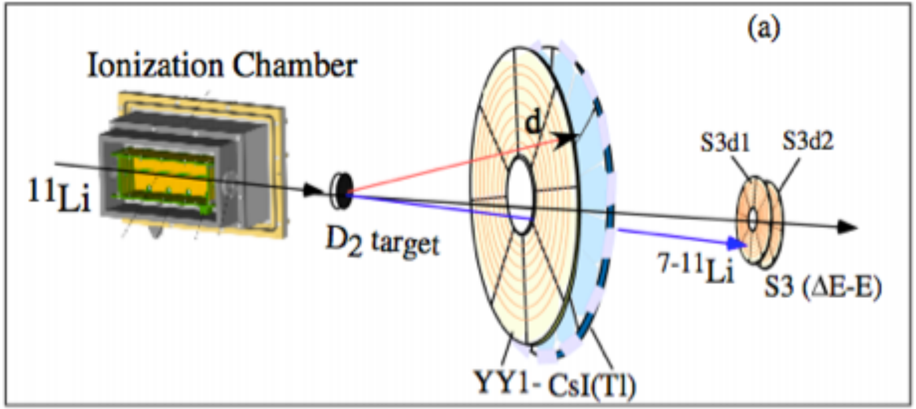
Nuclear physics aims to describe all isotopes of which we expect ~ 7000 to exist. Only 288 of those are stable.

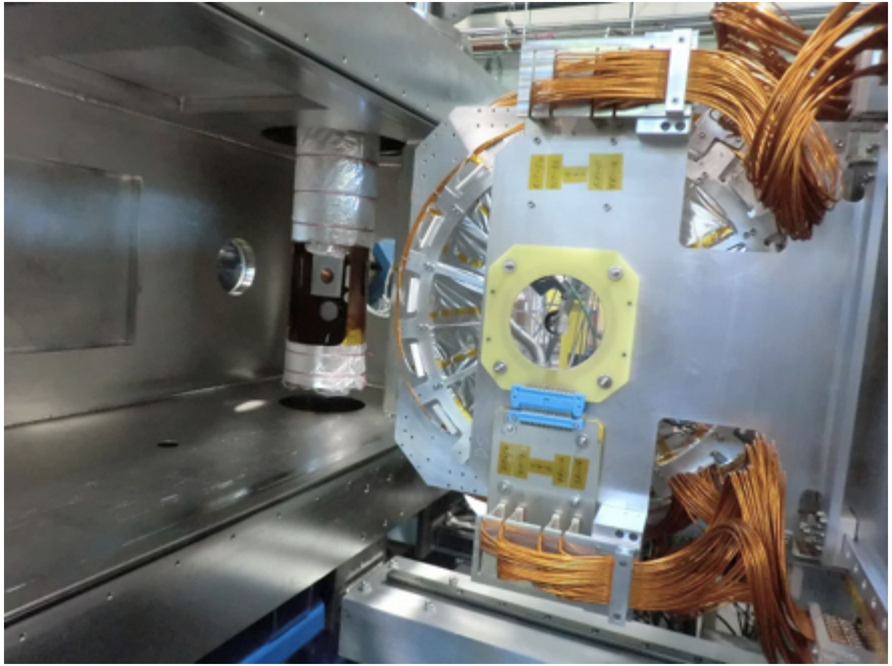
Currently we use different approaches for specific areas of the nuclear chart with finite range and limited predictability.

We seek to develop an approach/ theory that works everywhere and for all isotopes, the standard model for nuclear physics.

WHY:

- to explain what holds atomic nuclei together
- a full understanding of the nuclear strong force





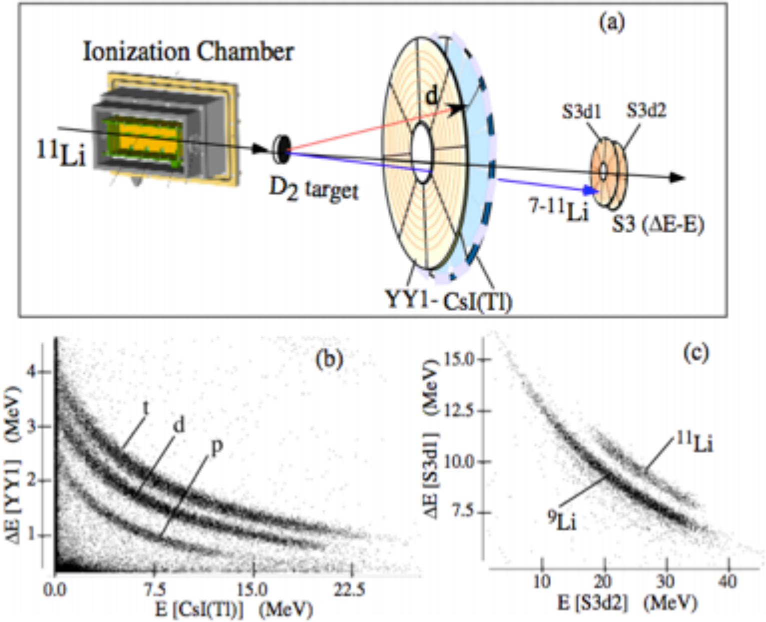
- Transmission ion chamber for beam identification
- Frozen gaseous target on thin Ag foil
- Si and CsI detectors for particle identification and angular distributions

IRIS: d(^{11}Li,d')^{11}Li'

PRL **114**, 192502 (2015) PHYSICAL REVIEW LETTERS week ending 15 MAY 2015

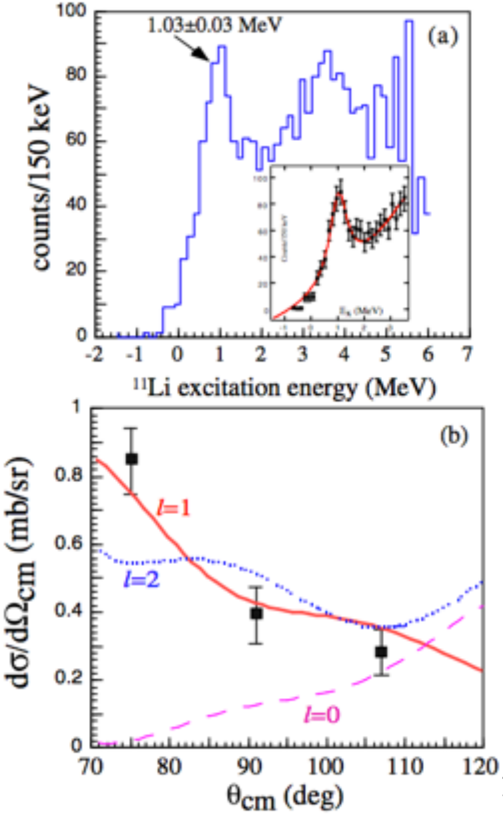
Evidence of Soft Dipole Resonance in ^{11}Li with Isoscalar Character

R. Kanungo, A. Sanetullaev *et al.*



First evidence of a dipole resonance in ^{11}Li having an isoscaler character.

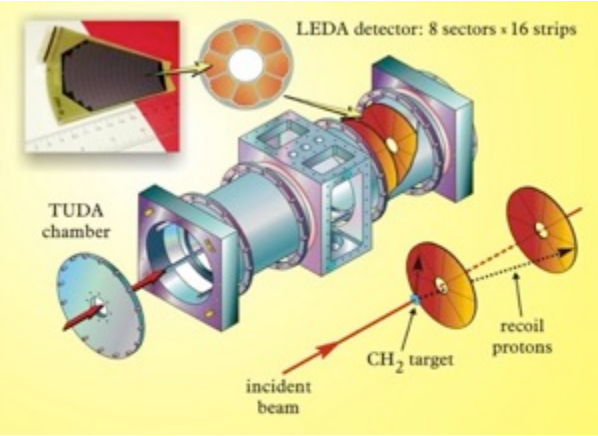
Provides stringent tests of *ab initio* theories and nuclear forces.

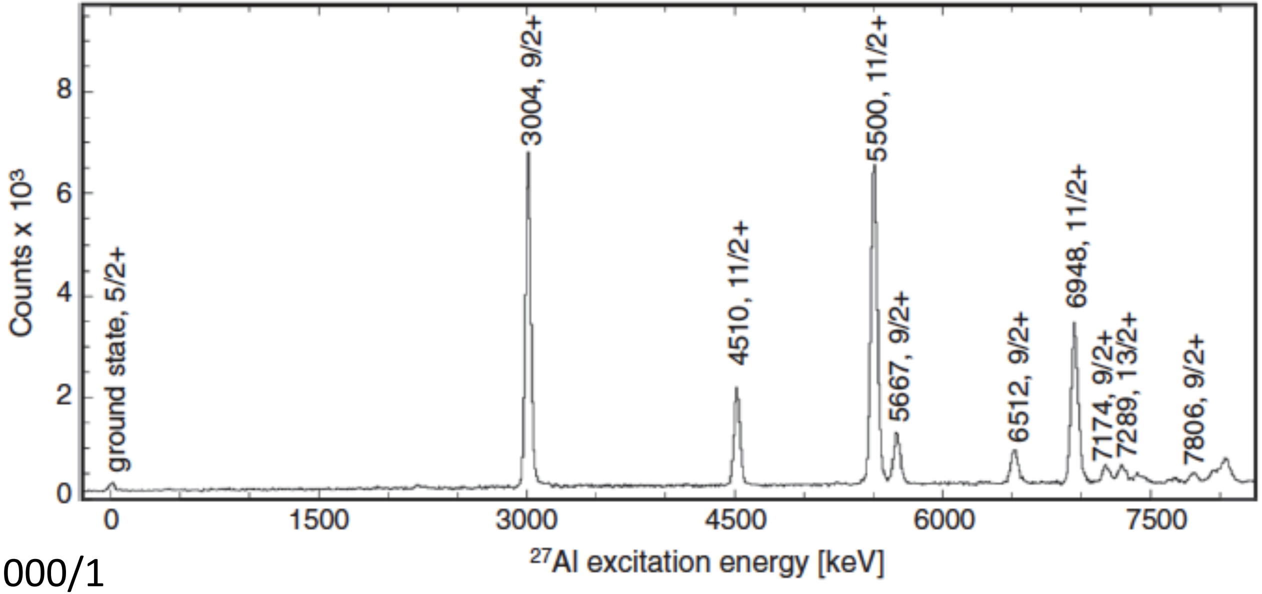


TUDA: $^{26g}Al(d,p)^{27}Al$

PRL 115, 062701 (2015) PHYSICAL REVIEW LETTERS week ending 7 AUGUST 2015

Inverse Kinematic Study of the $^{26g}Al(d,p)^{27}Al$ Reaction and Implications for Destruction of ^{26}Al in Wolf-Rayet and Asymptotic Giant Branch Stars





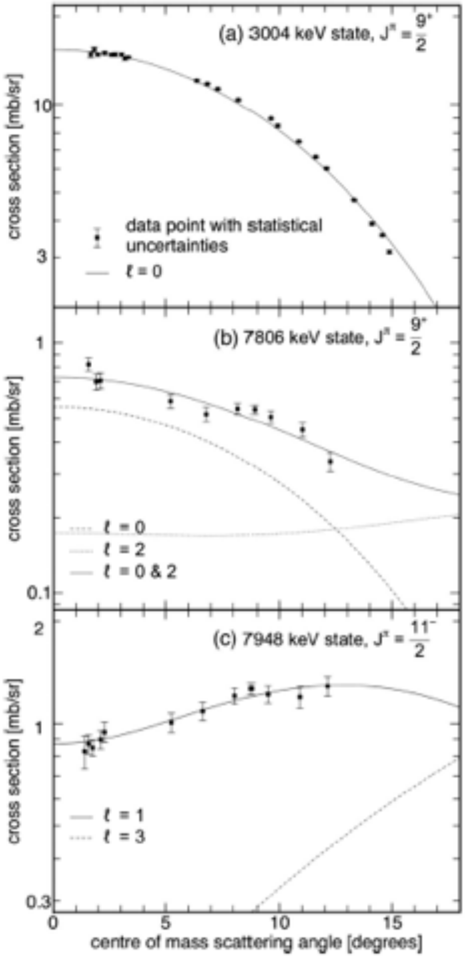
TUDA array

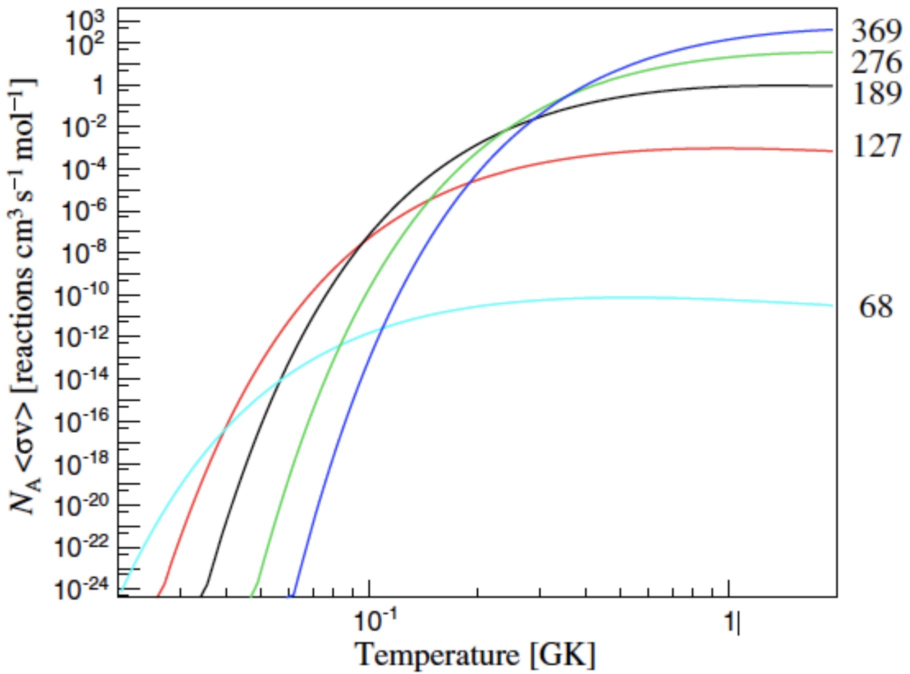
1pnA ^{26}Al at 6 AMeV with GS/IS=17,000/1

~50 μg=cm^2 thick CD_2 target

~40keV FWHM

TUDA: $^{26g}Al(d,p)^{27}Al$





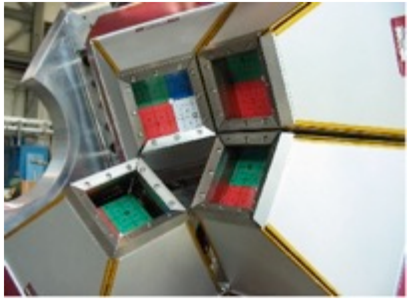
127 keV resonance in ^{27}Si determines the entire $^{26g}Al(p,\gamma)^{27}Si$ reaction rate over almost the complete temperature range of Wolf-Rayet stars and AGB stars.

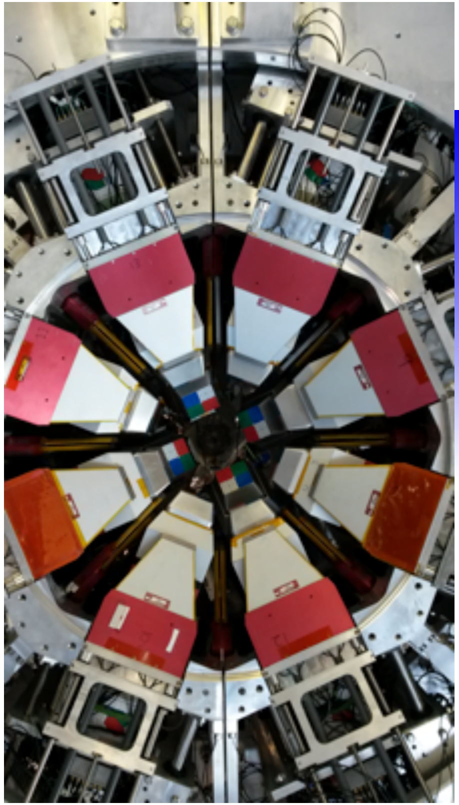
V. Margerin, G. Lotay *et al.*, PRL 115, 062701 (2015).

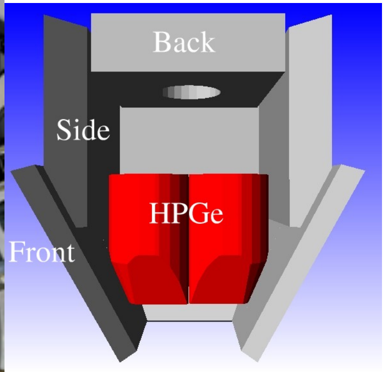
TRIUMF

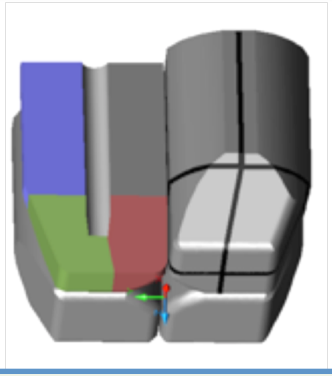
TIGRESS Facility

- TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer
- High energy-resolution, high efficiency gamma-ray detector array
- Up to 16 units of “clover” detectors
- 4 crystals per unit, 8 outer contacts per crystal, reconfigurable suppressor shields, Cold FET on core, warm FETs on segments
- Suit of ancillary detector systems for particle detection
- Studies with accelerated RIBs 0.5-15MeV/u







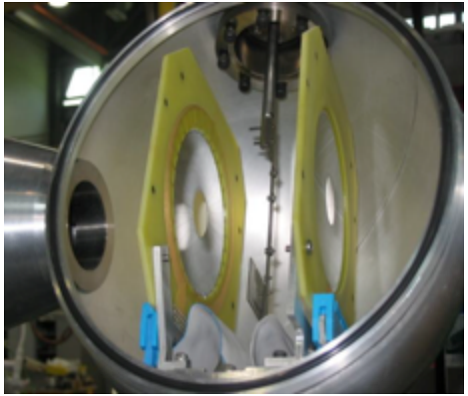


G. Hackman & C.E. Svensson, Hyperfine Int. ***225****, 251 (2014)*

Si detector arrays: Bambino and SHARC

BAMBINO: Collaboration with Lawrence Livermore Nat's Lab, U. of Rochester

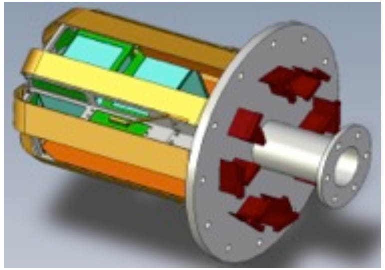
- 2 Si detectors for heavy-ion detection, TIG-10 readout
- Well suited to Coulex

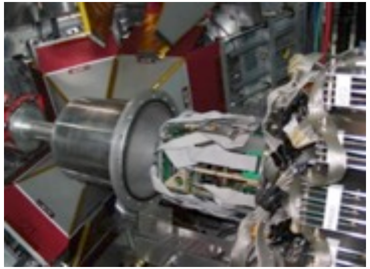


SHARC Silicon Highly-segmented Array for Reactions and Coulex

- U. York-LSU-CSM*-TIGRESS collaboration
- High granularity, full angular range coverage, dE-E telescopes, TIG-64 readout

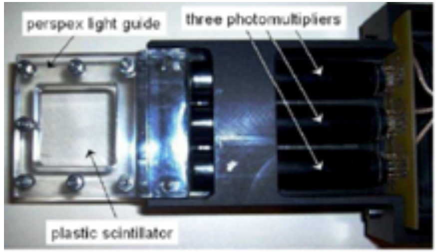
C.A. Diget et al, J. Inst. ***6****, P02005 (2011)*





- LPC-Caen Downstream thin plastic scintillator ("TRIFOIL") for transfer product ID/fusion-evaporation veto

G.L. Wilson et al, J. Phys. Conf. ***381****, 012097 (2012)*

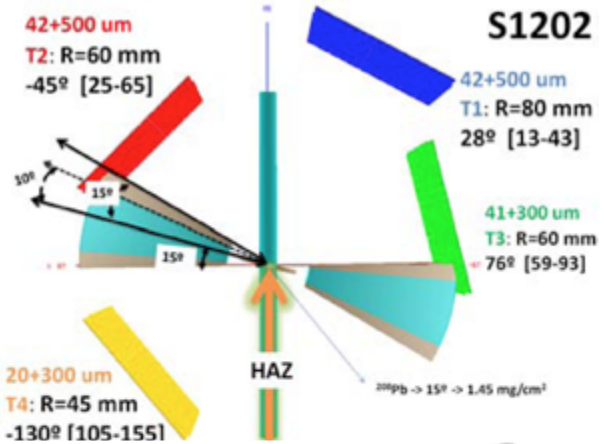


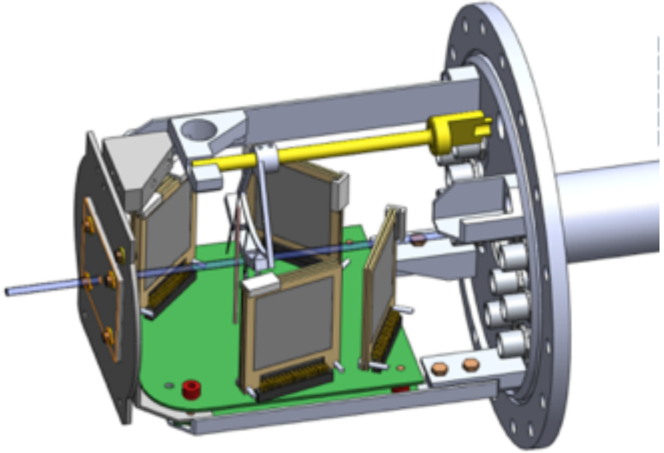
^{11}Be at 31.2 and 39.6 MeV

- ^{197}Au 1.9 mg/cm2 target
- Coulomb barrier ~40 MeV

- Charged particle telescope configuration optimized for this specific study
- 3 x DSSD 16x16 (40 μm) + pad (500 μm), 15 to 95 deg
- 1 x SSSD 16 (20 μm) + DSSD 16x16 (300 μm),
  105 to 150 deg lab

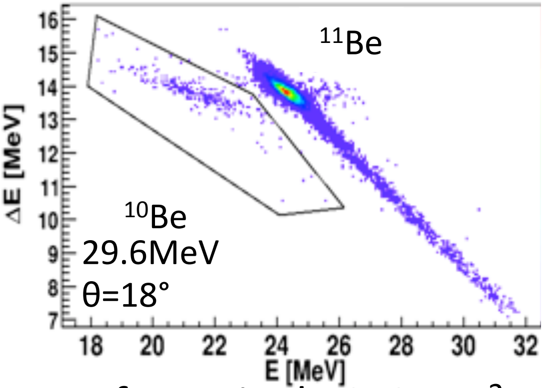
- HPGe: 12 clovers, 90 and 135 deg, high suppression mode

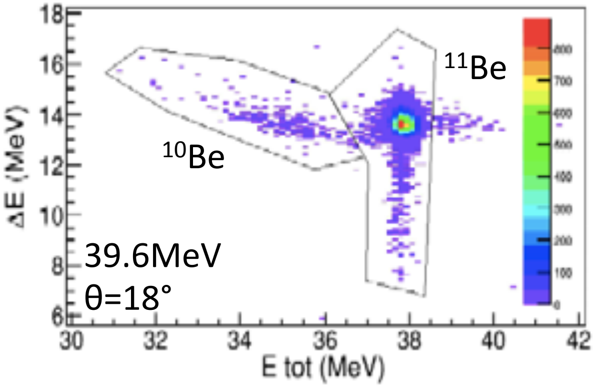




^{11}Be on ^{197}Au at TIGRESS

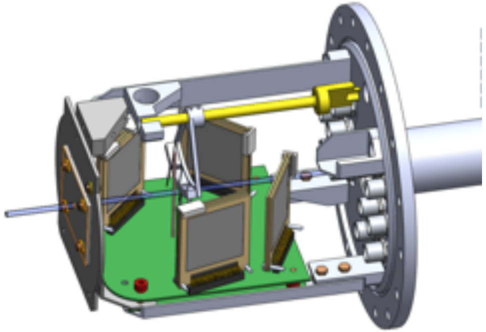
V. Pesudo, M.L.G. Borge et al., Accepted to PRL.

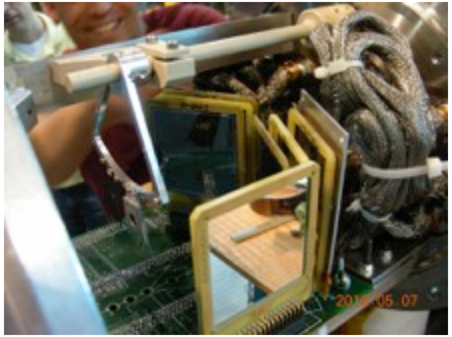


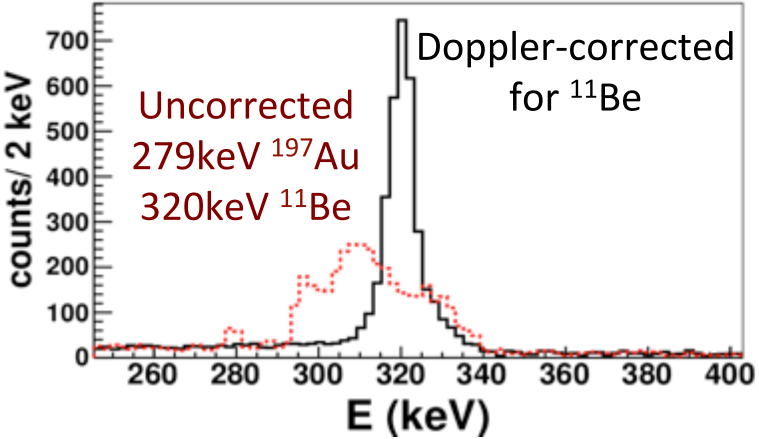


ΔE-E from single 3x3mm^2 pixel

- ^{10}Be from break-up.
- ^{11}Be quasi-elastic can be identified with the coincident 320keV gamma ray in TIGRESS

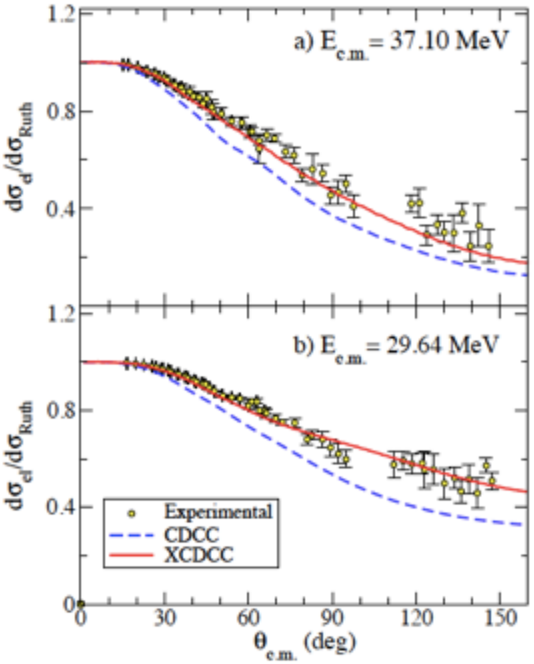




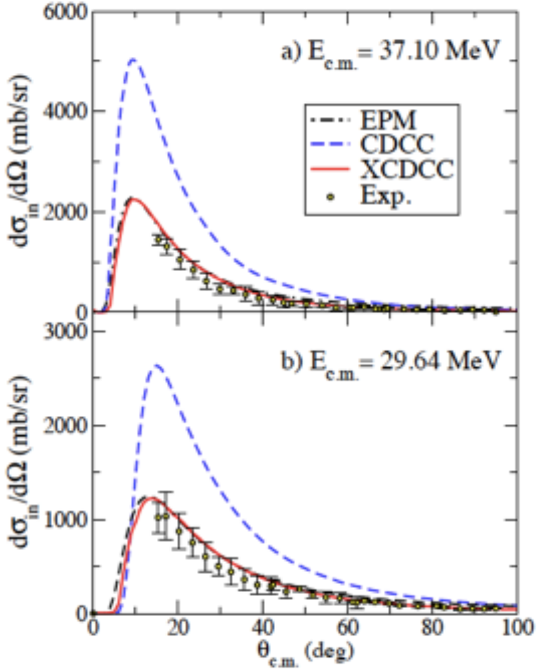


^{11}Be on ^{197}Au at TIGRESS

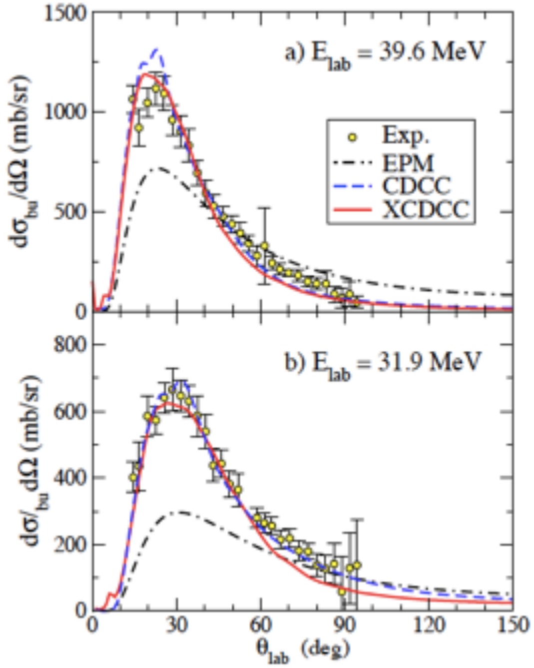
Elastic, ^{11}Be



Inelastic, ^{11}Be* - ^{11}Be+γ



Break-up – ^{10}Be+n



Structure of ^{11}Be:

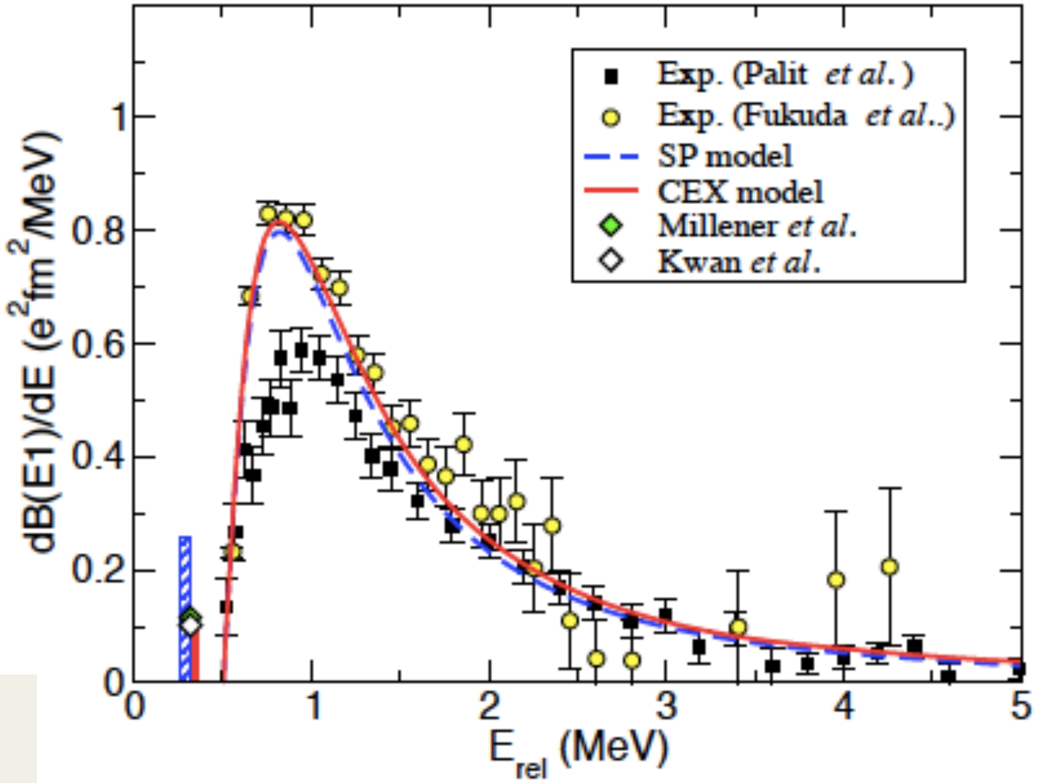
- (SP) Single Particle
- (CEX) Particle-plus-core model

Scattering observables:

- (EPM) Equivalent Photon Method (SP)
- (CDCC) Continuum-Discretized Coupled Channels (SP)
- (XCDCC) CDDC with core-halo entanglement (CEX)

V. Pesudo, M.L.G. Borge et al., Accepted to PRL.

B(E1) strength calculation – coupling of core and halo states is important

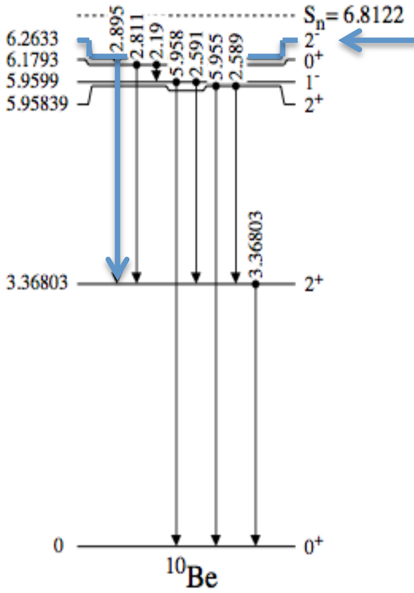


R. Palit et al., Phys. Rev. C 68, 4318 (2003).
N. Fukuda et al., Phys. Rev. C 70, 054606 (2004).
D. Millener et al., Phys. Rev. C 28, 497 (1983).
E. Kwan et al., Phys. Lett. B 732, 210 (2014).

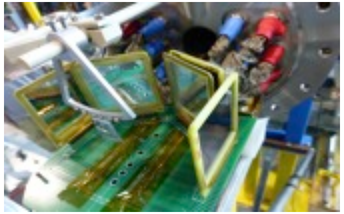
Other TIGRESS data: $^{11}Be(p,d)$ @ 110 MeV and $^{11}Be(^{9}Be,x)$ @ 30, 55 MeV

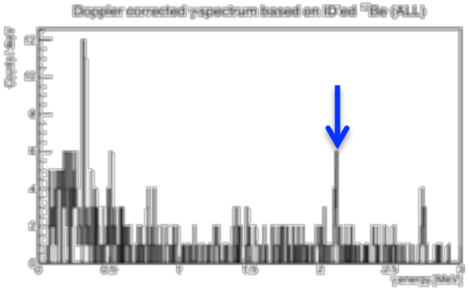
Goal to investigate extended (halo? Cluster?) structures in ^{10}Be, ^{12}Be

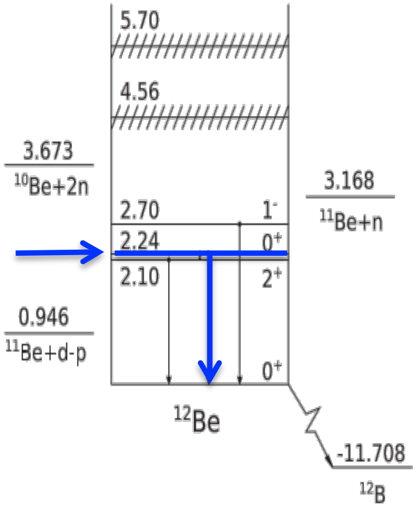
K. Kuhn, Ph.D. candidate, CSM, in progress



R. Braid, Ph.D. candidate, CSM, in progress







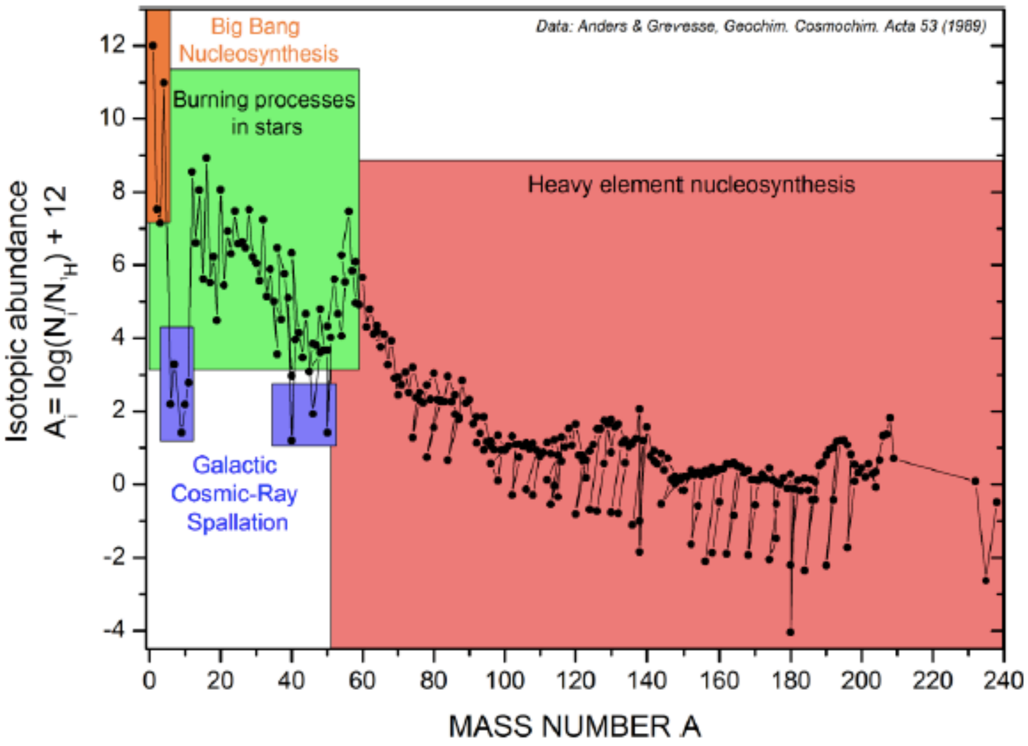
Origin of the elements

Nuclear astrophysics aims at understanding the origin of all stable isotopes as observed in the "solar abundance curve"

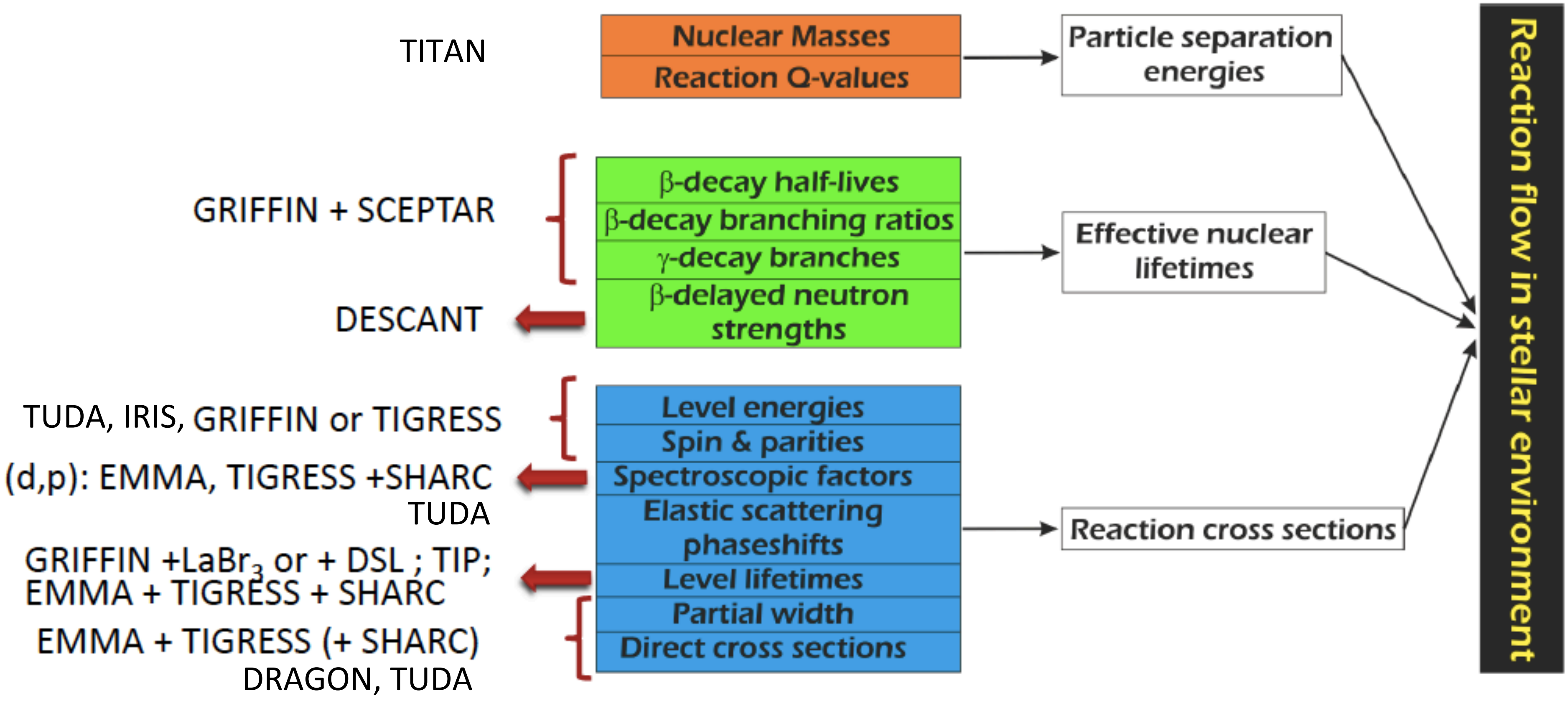
"Heavy element nucleosynthesis" summarizes several reaction mechanisms producing all elements heavier than Fe:

- "slow" neutron capture process
- "rapid" neutron capture process
- "intermediate" neutron capture process
- Production of proton-rich isotopes

$$N_{\odot} = N_s + N_r + N_i + N_p$$

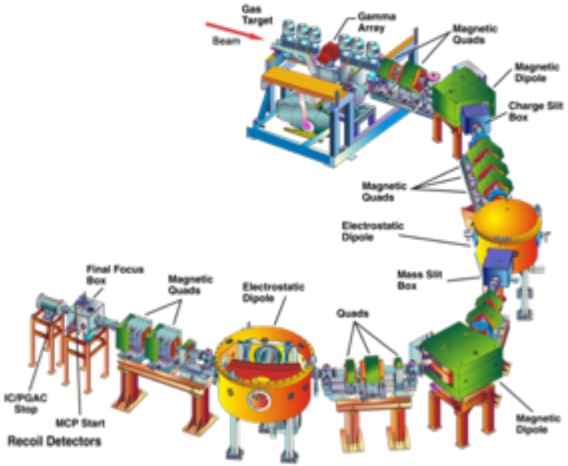


Nuclear Physics Data from ISAC for Astrophysics



TRIUMF

Direct Capture Cross Section measurements at DRAGON



Reaction	Motivation	Intensity (s^{-1})	Purity (beam:cont.)
$^{21}Na(p,\gamma)^{22}Mg$	1.275 MeV line emission in ONe novae	5×10^{9}	100%
$^{12}C(\alpha,\gamma)^{16}O$	Helium burning in red giants	6×10^{11}	
$^{26g}Al(p,\gamma)^{27}Si$	Nova contribution to galactic ^{26}Al	3×10^{9}	30,000:1
$^{12}C(^{12}C,\gamma)^{24}Mg$	Nuclear cluster models	3×10^{11}	
$^{40}Ca(\alpha,\gamma)^{44}Ti$	Production of ^{44}Ti in SNII	3×10^{11}	10,000:1 – 200:1
$^{23}Mg(p,\gamma)^{24}Al$	1.275 MeV line emission in ONe novae	5×10^{7}	1:20 – 1:1,000
$^{17}O(\alpha,\gamma)^{21}Ne$	Neutron poison in massive stars	1×10^{12}	
$^{18}F(p,\gamma)^{19}Ne$	511 keV line emission in ONe novae	2×10^{6}	100:1
$^{33}S(p,\gamma)^{34}Cl$	S isotopic ratios in nova grains	1×10^{10}	
$^{16}O(\alpha,\gamma)^{20}Ne$	Stellar helium burning	1×10^{12}	
$^{17}O(p,\gamma)^{18}F$	Explosive hydrogen burning in novae	1×10^{12}	
$^{3}He(\alpha,\gamma)^{7}Be$	Solar neutrino spectrum	5×10^{11}	
$^{58}Ni(p,\gamma)^{59}Cu$	High mass tests (p-process, XRB)	6×10^{9}	
$^{26m}Al(p,\gamma)^{27}Si$	SNII contribution to galactic ^{26}Al	2×10^{5}	1:10,000
$^{38}K(p,\gamma)^{39}Ca$	Ca/K/Ar production in novae	2×10^{7}	1:1
$^{19}Ne(p,\gamma)^{20}Na$	^{19}F abundance in nova ejecta	2×10^{7}	1:1 to 4:1
$^{22}Ne(p,\gamma)^{23}Na$	NeNa cycle; explosive H burning in classical novae	2×10^{12}	

7 RIB

10 Stable beam

^{19}F observed in nova ejecta
→ Direct comparison of experimental results with astronomical data!
→ Probe nucleosynthesis models!

^{19}F is **only stable fluorine** isotope

→ No complication in spectroscopy by ^{18}F contribution ($T_{1/2}$ = 158 min, 511 keV & continuum)

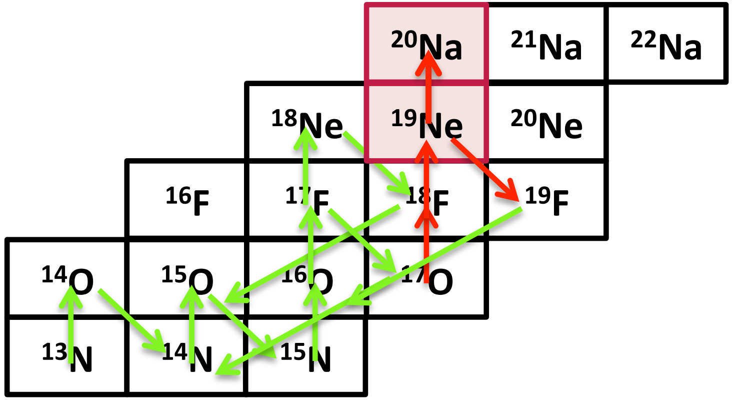
→ Fluorine observed in ejecta exclusively from ^{19}F contribution

The $^{19}Ne(p,\gamma)^{20}Na$ reaction – Relevance for ONe novae

- Experimental determination of **reaction rates → nova models**
- **Production & destruction** of ^{19}F
- ^{19}F is produced via $\mathbf{^{17}O(p,\gamma)^{18}F(p,\gamma)^{19}Ne(\beta^+)^{19}F}$
- **But:** At high peak temperatures (~0.4 GK) ^{19}F synthesis can be **bypassed** via $\mathbf{^{19}Ne(p,\gamma)^{20}Na}$ reaction ("Leakage" out of hot CNO cycle)

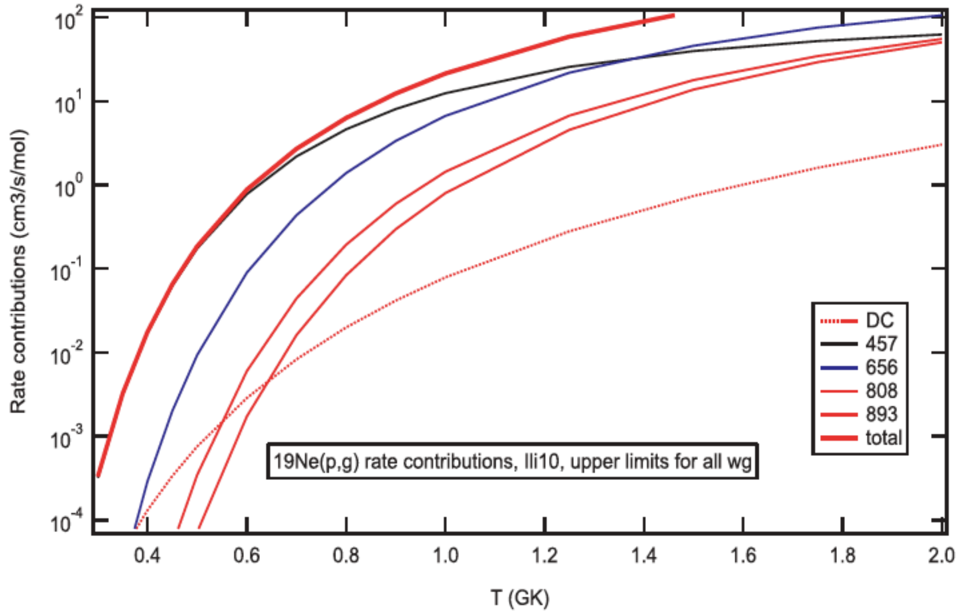
- High uncertainty in reaction rate
- Rate variations may affect **^{19}F abundance** by up to a **factor of 7**! [2]

→ Essential to constrain uncertainty!



457 keV resonance – contribution to stellar reaction rate

- **^{19}Ne(*p*,γ)^{20}Na** reaction rate dominated by **single low-energy resonance** at **E_R~457 keV** above proton threshold (2190.1(11) keV) in ^{20}Na
- **Direct** experimental determination of → **Probe for theoretical models**



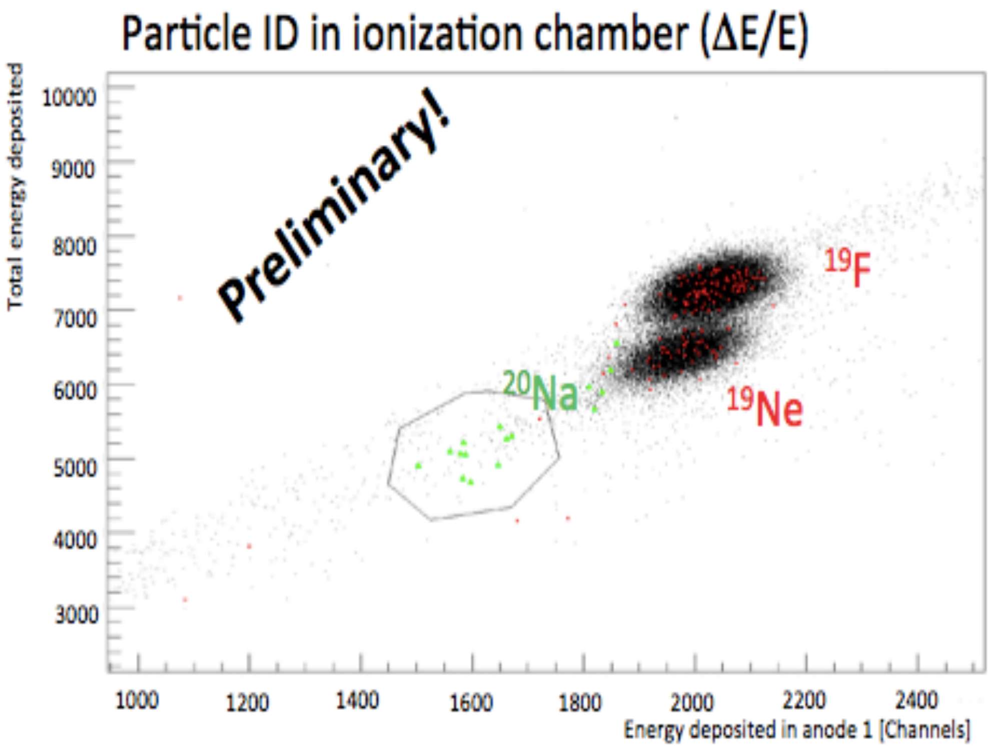
BUT:

Exact resonance strength and J^{π} have been subject to **debate for 2 decades!**

Figure from G. Lotay, C. Ruiz, U. Greife, TRIUMF research proposal (2015)

Preliminary results – Particle ID

Analysis in progress! (Collaboration with University of Surrey)



- **Black:** Raw singles events
- 2 main clusters:

  ^{19}F & ^{19}Ne

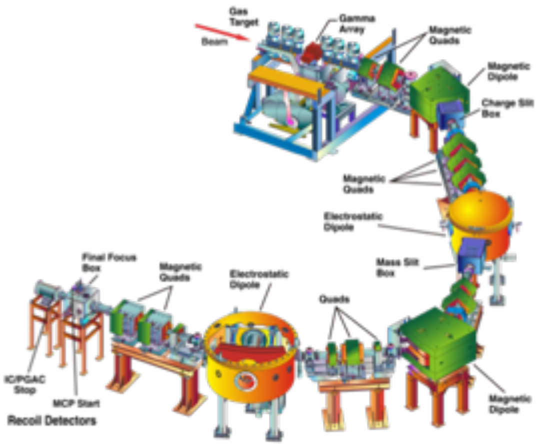
- **Red:** Raw coincidence events
- **Green:** ^{19}Ne(p,γ)^{20}Na recoils

457 keV resonance likely **stronger** than previous upper limit!

DRAGON: $^{38}K(p,\gamma)^{39}Ca$

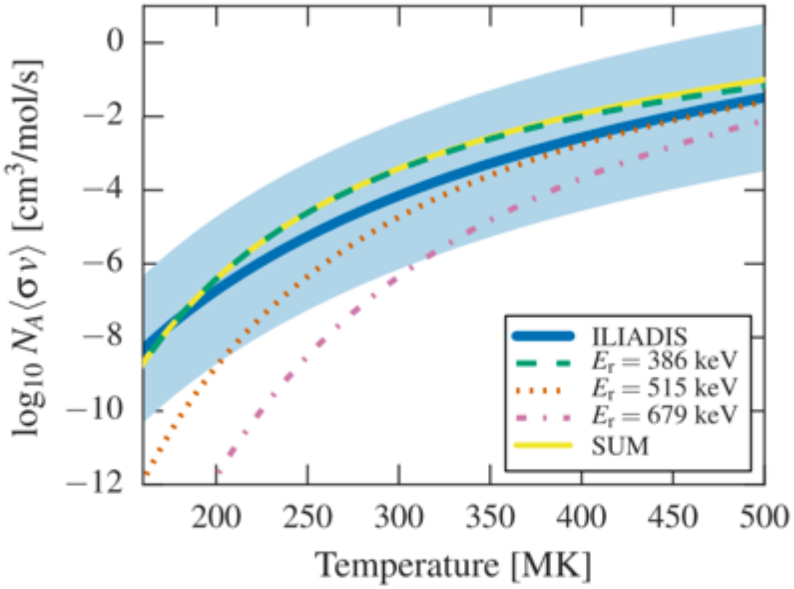
PRL **116,** 132701 (2016) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2016

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



First experimental measurement of this reaction rate.

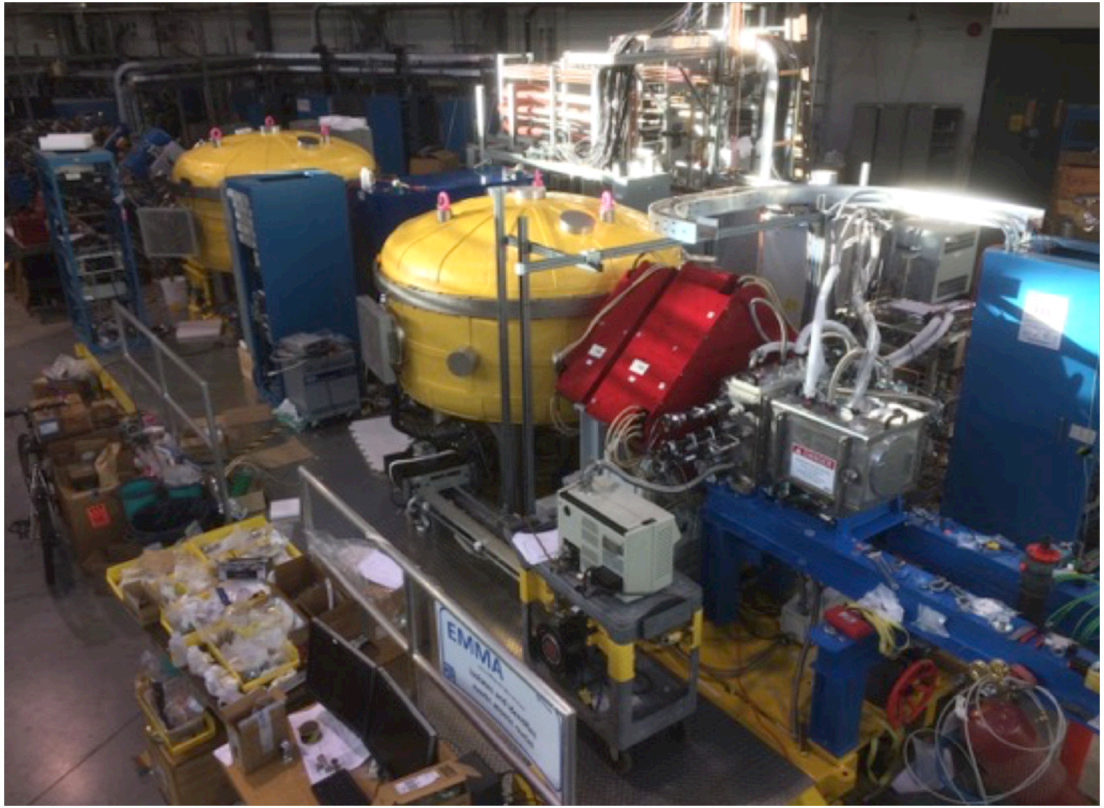
Constrains the rate of $^{38}K(p,\gamma)^{39}Ca$ in ONe nova and significantly reduces uncertainty in ^{38}Ar and ^{40}Ca abundances.



First charge-bred beam to DRAGON. Heaviest RIB direct radiative capture measurement.

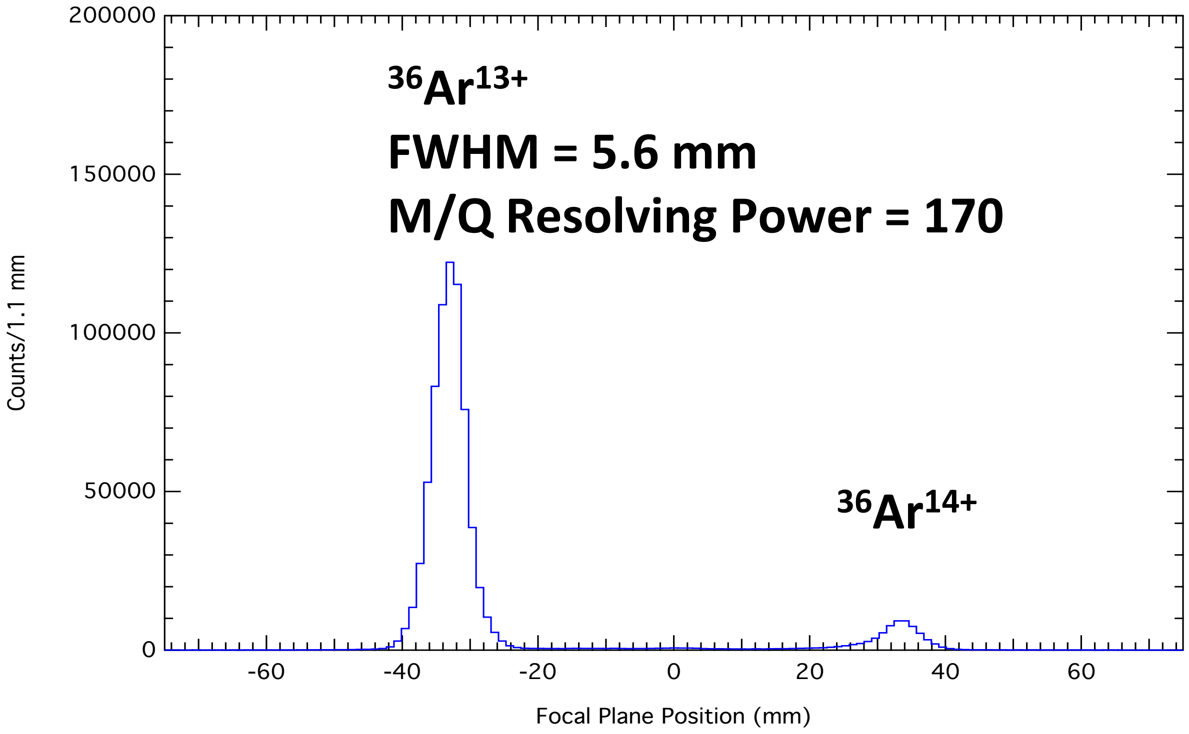
EMMA Installed

- Installation of the Electromagnetic Mass Analyzer EMMA completed in TRIUMF's ISAC-II experimental hall just in time for December 16th, 2016 beam time
- Designed to spatially separate reaction products from beam, disperse them according to mass/charge; focuses products in angle and energy



Successful Initial Test of EMMA

- Bombarded thick Au foil with 80 MeV ^{36}Ar beam
- Multiply scattered beam with large angular and energy spreads dispersed according to mass/charge ratios
- Measured mass/charge dispersion & resolving power found to be consistent with ion optical calculations
- Set for $^{197}Au^{9+}$, observed single mass peak, no background in hour-long run with 10^9 ions/s on target implying hardware beam suppression > 10^{12}

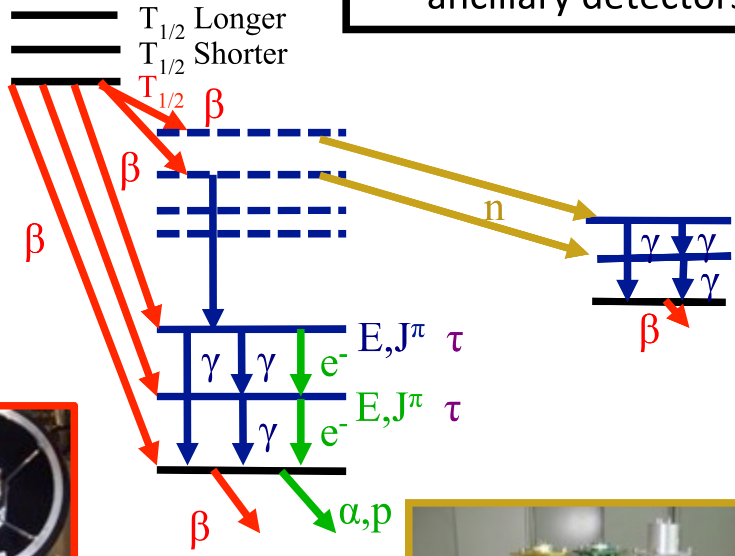


EMMA's First Mass/Charge Spectrum

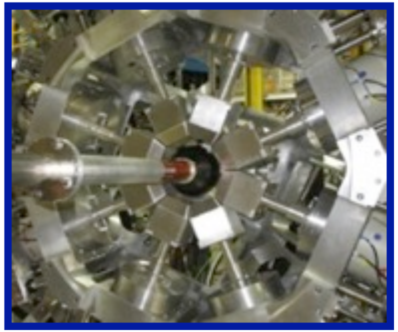
GRIFFIN: Sensitive Decay Spectroscopy

Fast, in-vacuum tape system

Enhances decay of interest



GRIFFIN couples with a powerful suite of ancillary detectors



HPGe: 16 Clovers

Detect gamma rays and determines branching ratios, multipolarities and mixing ratios

$LaBr_3$: 8 $LaBr_3$

Fast-timing of photons to measure level lifetimes

Zero-Degree Fast scintillator

Fast-timing signal for betas

SCEPTAR: 10+10 plastic scintillators

Detects beta decays and determines branching ratios

DESCANT Neutron array

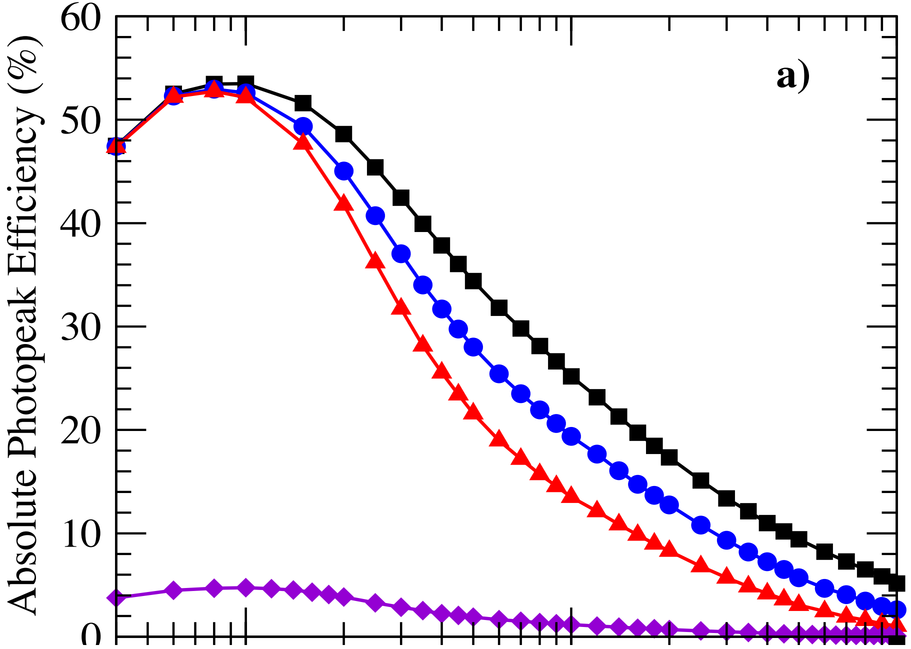
Detects neutrons to measure beta-delayed neutron branching ratios

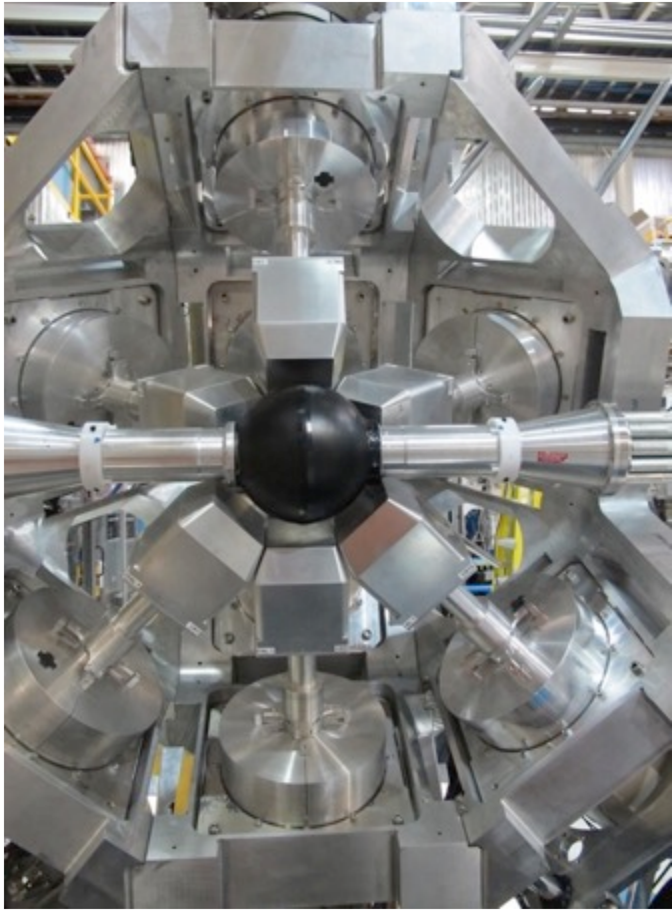
PACES: 5 Cooled Si(Li)s

Detects Internal Conversion Electrons and alphas/protons

GRIFFIN HPGe Clover Detectors

A close-packed array of 16 large-volume HPGe Clover detectors, 64 crystals

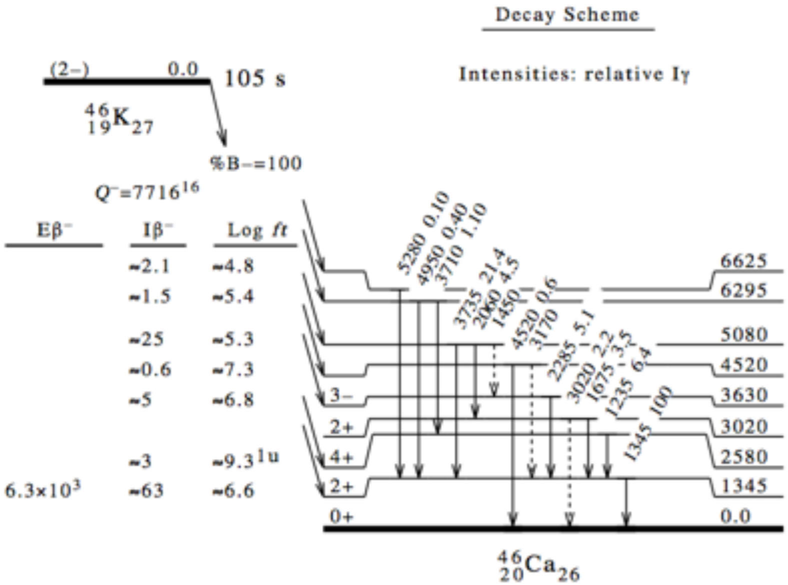


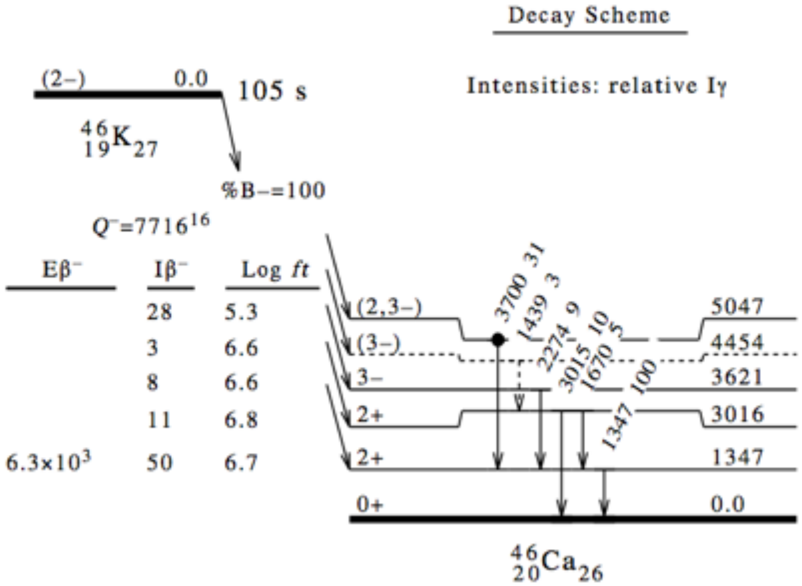


4096 crystal pairs at 52 unique angles for γ-γ angular correlations

^{46}Ca Level Structure via ^{46}K β Decay

Two previous beta decay experiments from the 1960's



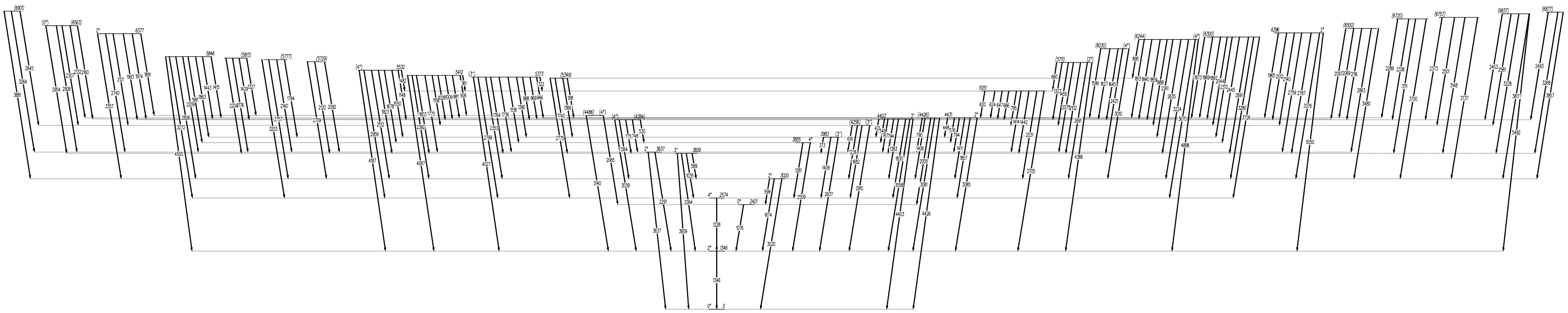


B. Parsa and G. Gordon, Phys. Lett. 2, 269 (1966).
M. Yagi et al., Laboratory Nucl. Sci., Tohoku Univ. 1, 60 (1968).

TRIUMF

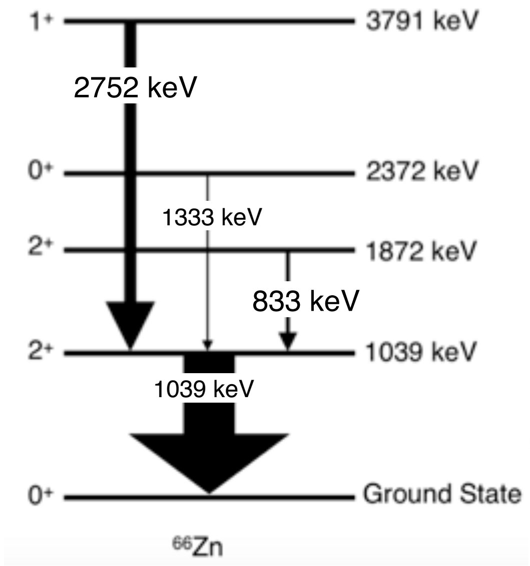
^{46}Ca Level Structure via ^{46}K β Decay

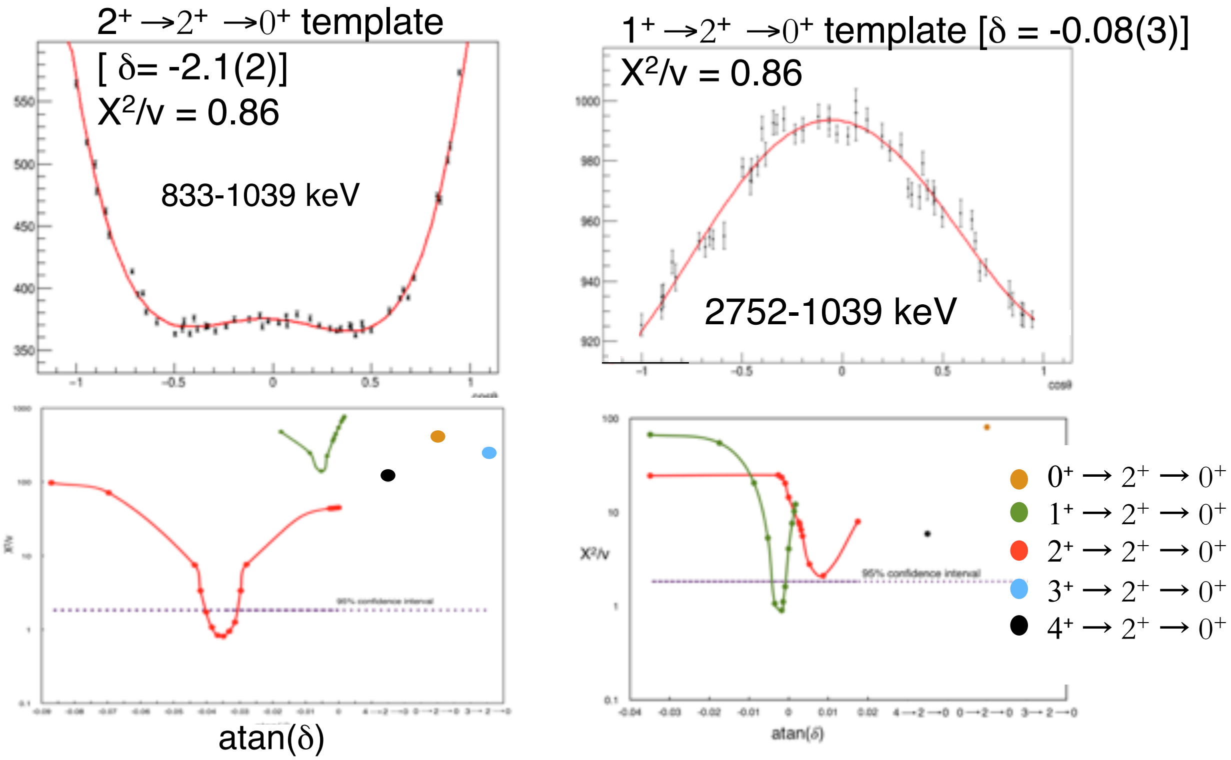
^{46}Ca level scheme from 1.5 days of ^{46}K beam to GRIFFIN



- ≈ 200 new gamma-ray transitions placed between 45 excited states
- States observed to within 815keV of the 7.7MeV *Q*-value.
- Branching ratios observed down to 10^{-3}
- Weakest gamma ray observed has intensity of 0.0015% that of the 2_1^+ to 0_1^+ transition.
- Performing new shell model calculations and γ–γ angular correlation analysis
- Ph.D. thesis defended by J. Pore, Simon Fraser University, in November 2016.

Gamma-Gamma Angular Correlation Analysis in ^{66}Ga Decay

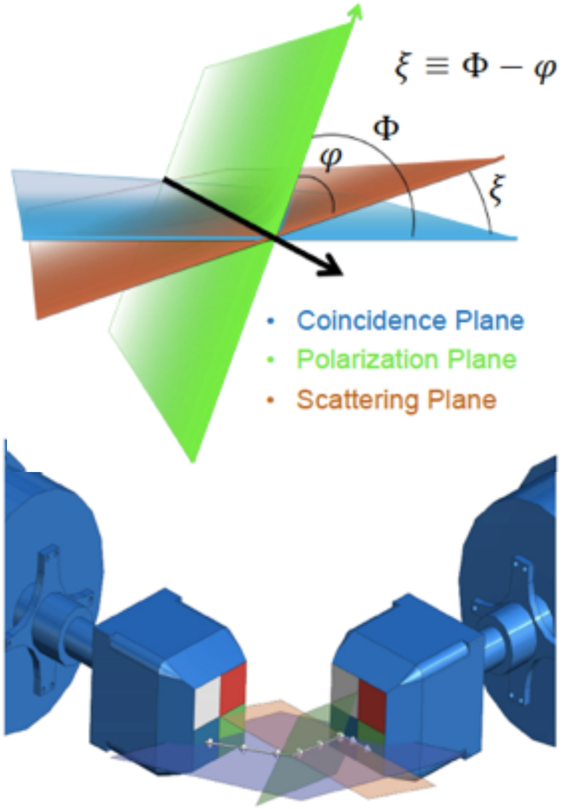




Development of γ–γ angular correlation analysis techniques with GRIFFIN using ^{66}Ga radioactive beam.

M.Sc. Thesis, A. MacLean, Guelph 2016

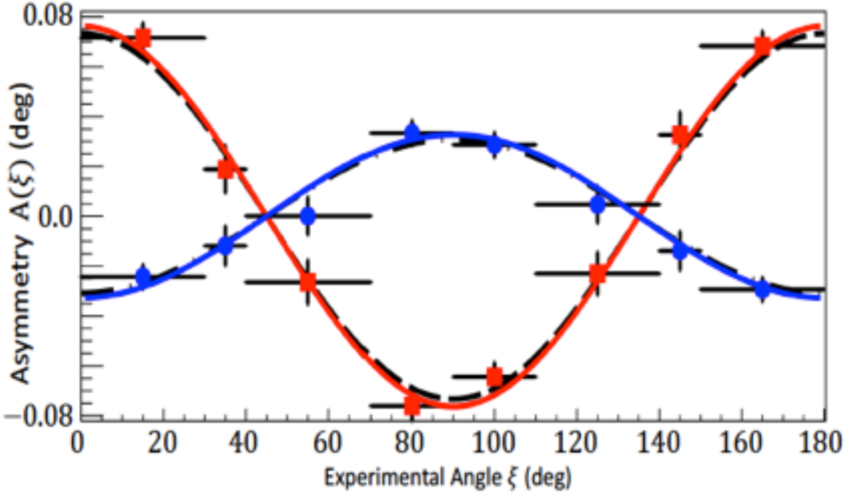
Compton Polarimetry using GRIFFIN



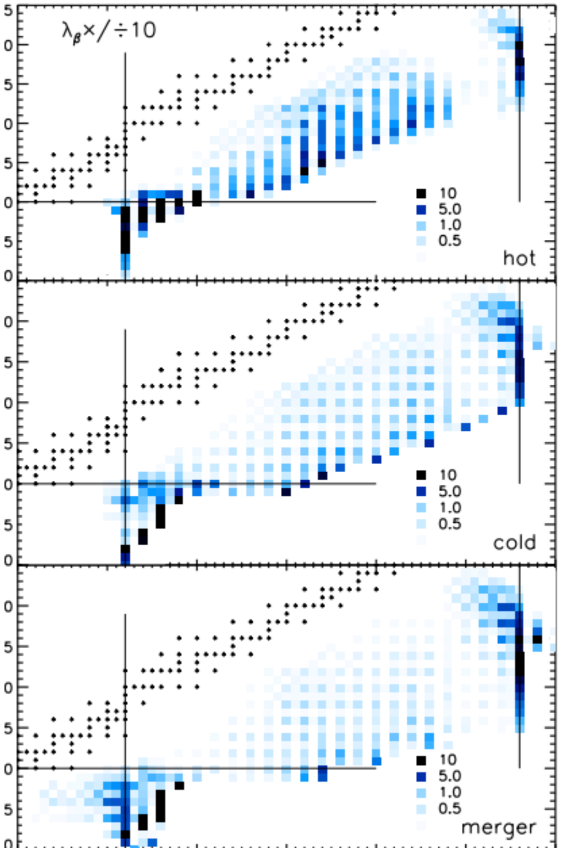
Dan Southall, TRIUMF research student, 2016

Define Polarization plane from γ–γ coincidence detection. Then examine azimuthal scattering angle to determine electric or magnetic nature of the radiation.

^{207}Bi Example: Red=567keV *E2*
Blue=1064keV *M4+E5*, δ_1=+0.03



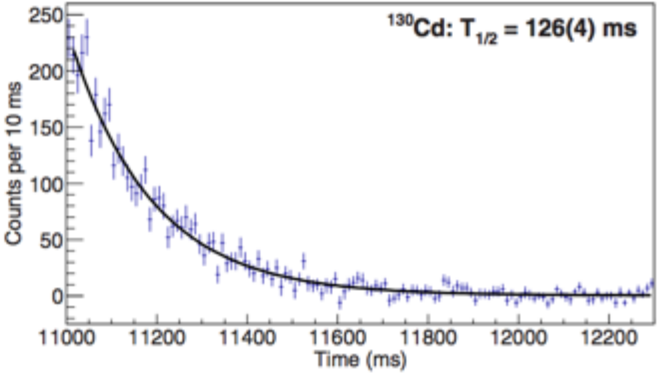
GRIFFIN: $^{128,129,130}Cd$ β-decay



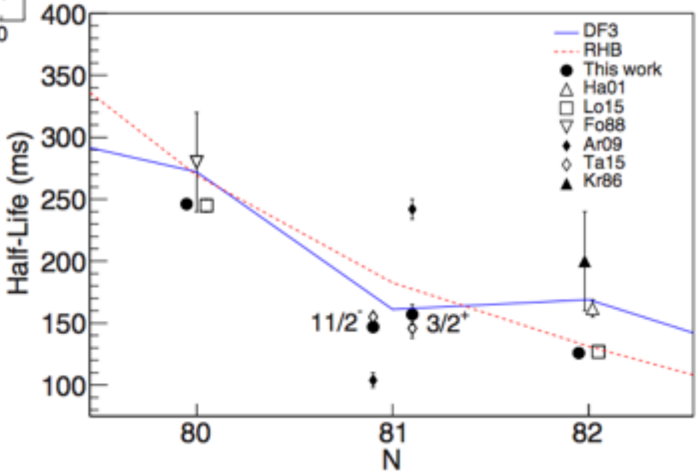
PHYSICAL REVIEW C **93**, 062801(R) (2016)

RAPID COMMUNICATIONS

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



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



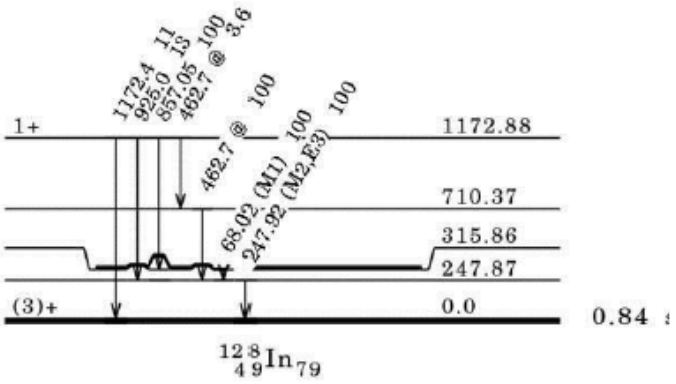
G. Lorusso et al. PRL 114 192501 (2015)
M. Mumpower *et al*., Prog.Part.Nucl.Phys. 86, 86 (2016)

New spectroscopic information in ^{128}In from ^{128}Cd beta decay

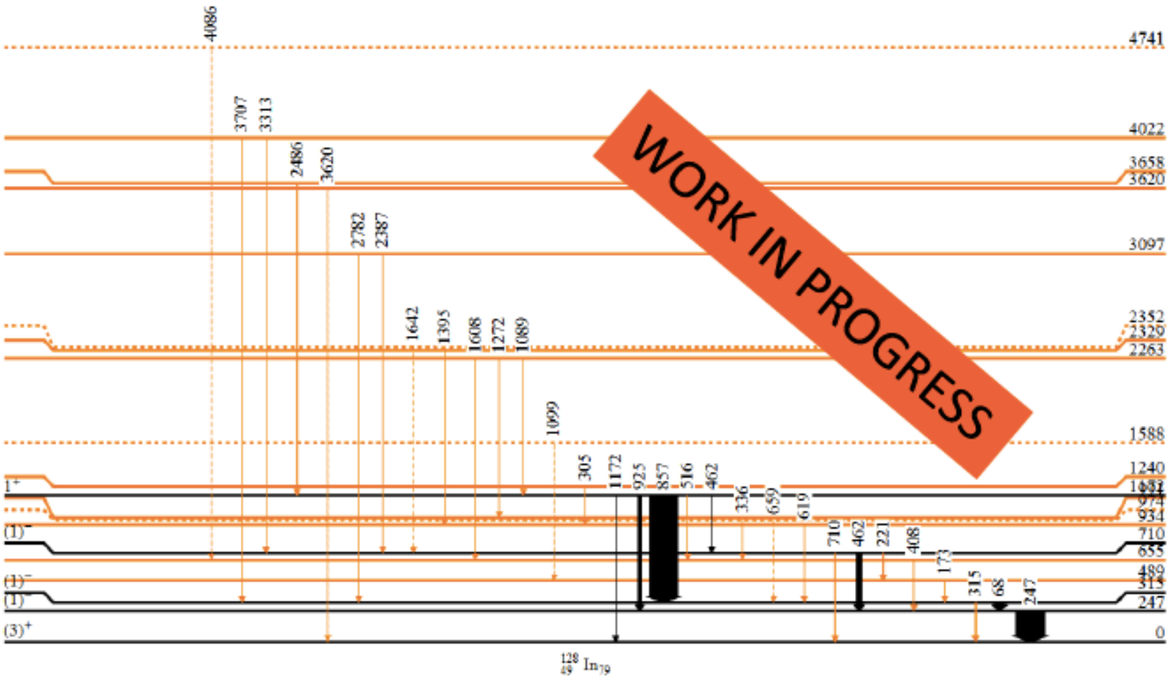
- PhD Nikita Bernier (UBC/ TRIUMF)

New: 23 new transitions, 15 new states

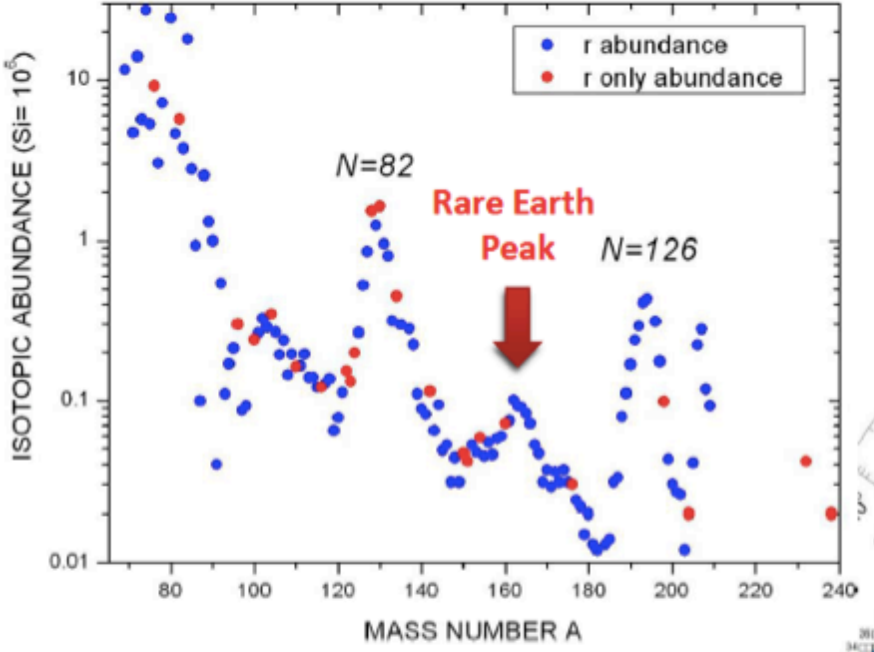
Before



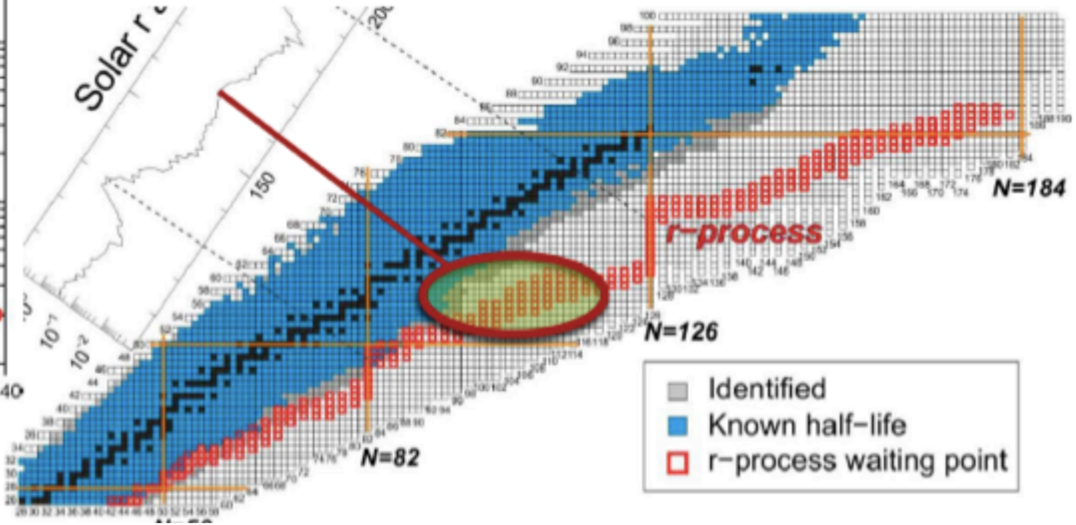
B. Fogelberg et al., Proc. Int. Conf. Nucl. Data for Sci. and Techn., 837 (1988).



Formation of the 'Rare-Earth Peak'



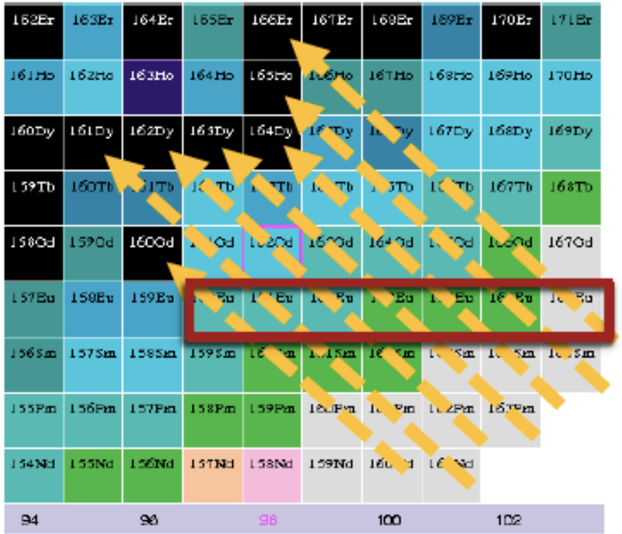
- Investigation of neutron-rich rare-earth metals
- Formation of the A≈165 r-process mini-peak
- Presently "Terra Incognita"
- Isotopes below mid-shell nucleus ^{170}Dy (Z=66, N=104)

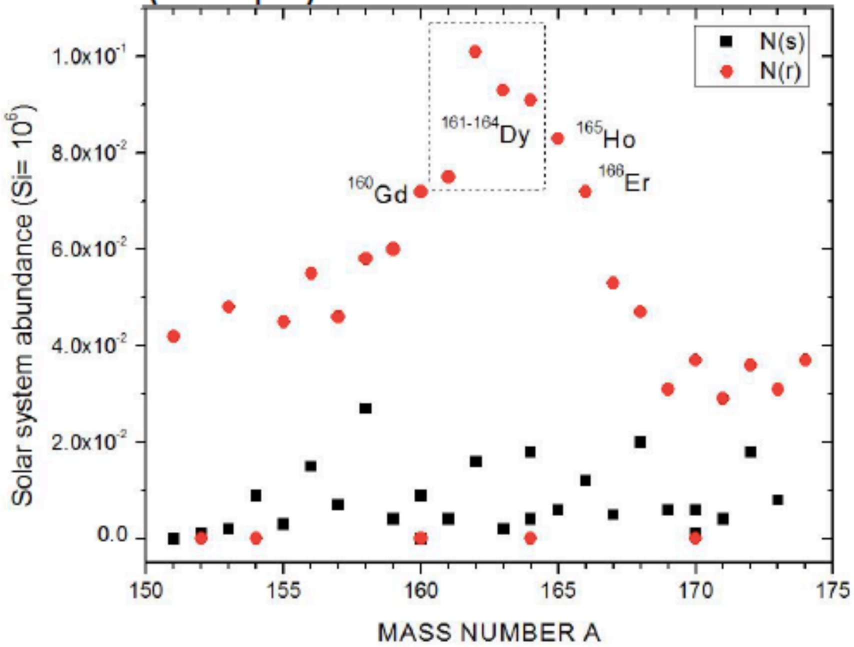


Formation of the ‘Rare-Earth Peak’

S1625: “Decay spectroscopy of neutron-rich $^{160-166}$Eu isotopes with GRIFFIN” Spokespersons: I. Dillmann (TRIUMF), P.E. Garrett (Guelph)

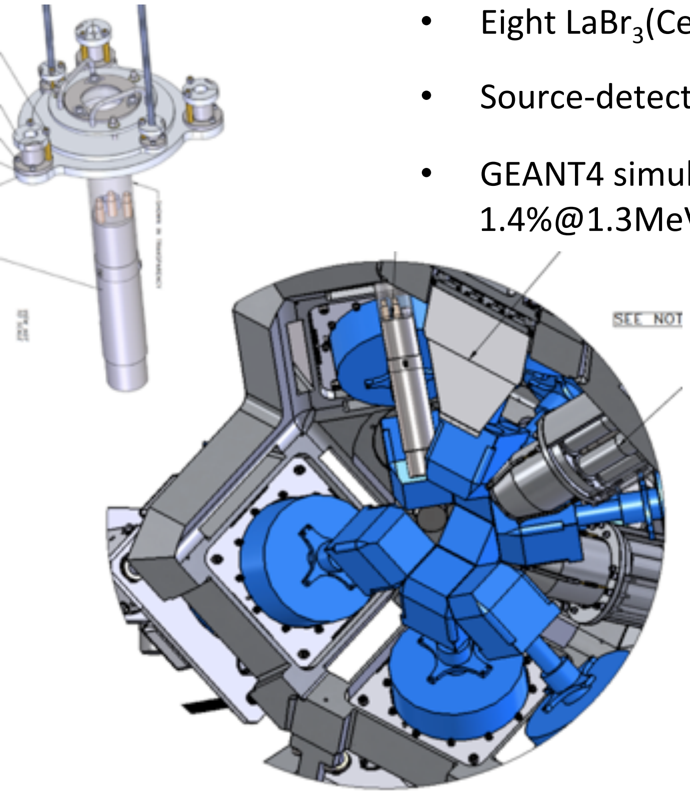
- To understand the formation of the REP, we need to understand the isotopes in the decay chains:



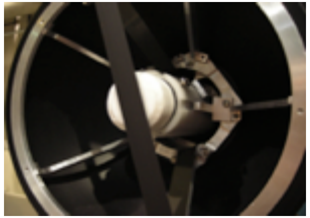


Data from Sneden et al., Annu. Rev. Astron. Astrophys. 2008

$LaBr_3$ Fast-Scintillator Array for Excited-State Lifetimes



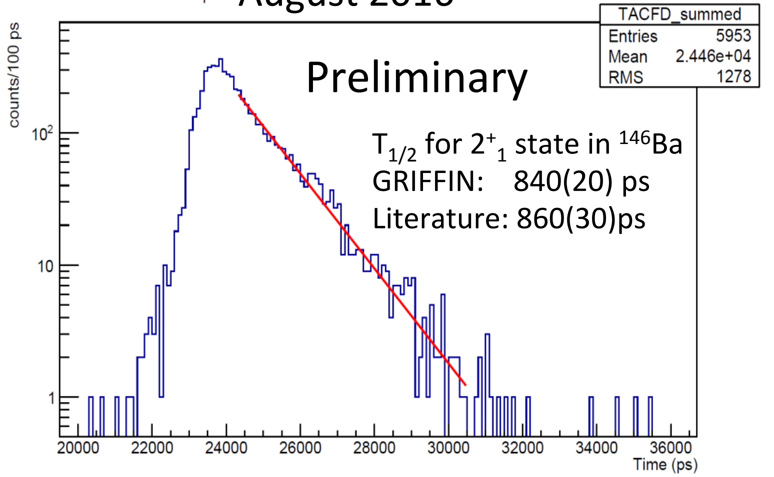
- Eight $LaBr_3$(Ce) 2”x2” cylindrical crystal
- Source-detector distance=12.5 cm.
- GEANT4 simulated efficiency 1.4%@1.3MeV



- Hybrid analogue + digital electronics, excellent time resolution
- Effort led by Bruno Olaizola, University of Guelph

^{146}Cs β decay: GRIFFIN +DESCANT +$LaBr_3$

August 2016



The Advanced Rare IsotopE Laboratory 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

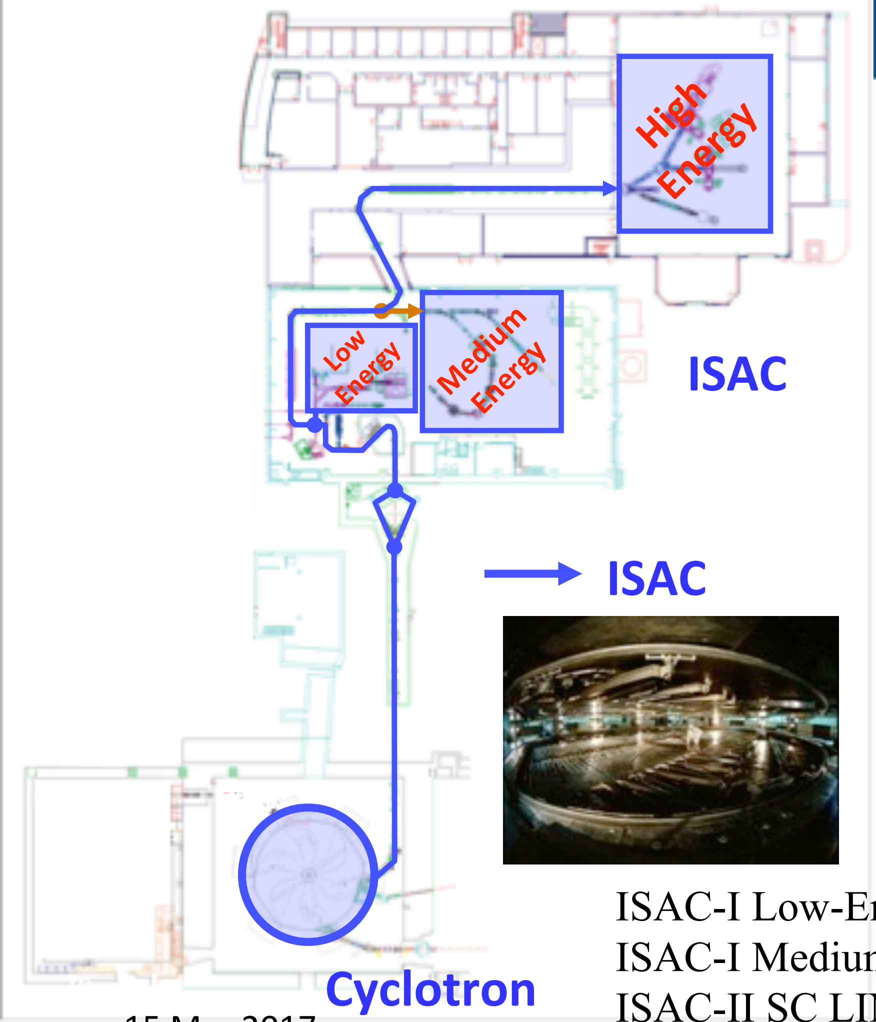
TRIUMF-ISAC

Isotope Separator and ACcelerator

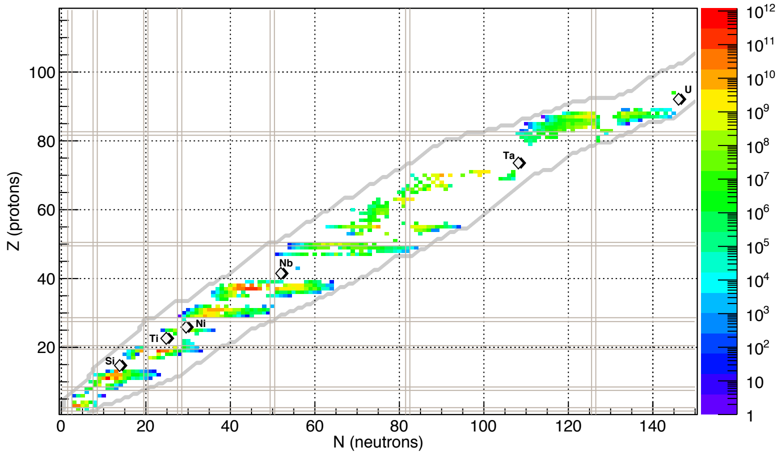
1 RIB delivery to experiments

500MeV p^+ at 100μA on ISOL target

SiC, NiO, Nb, ZrC, Ta, UC_x Targets
Surface, FEBIAD, IG-LIS ion sources



→ ISAC

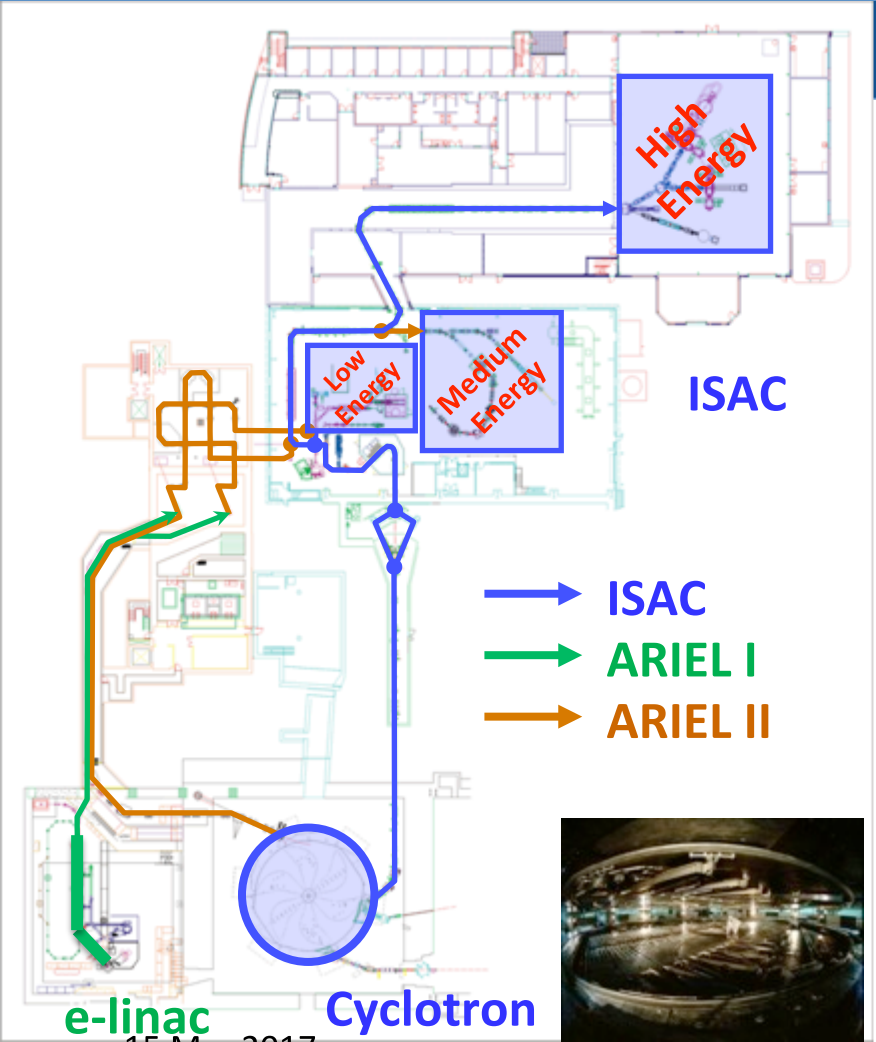


ISAC-I Low-Energy <60keV — Ground state + decay, material science
ISAC-I Medium E <1.5MeV/u — Astrophysics
ISAC-II SC LINAC <10MeV/u — Nuclear reactions and structure

TRIUMF-ARIEL

Advanced Rare-IsotopE Laboratory

1 RIB ➔ 3 simultaneous RIBs



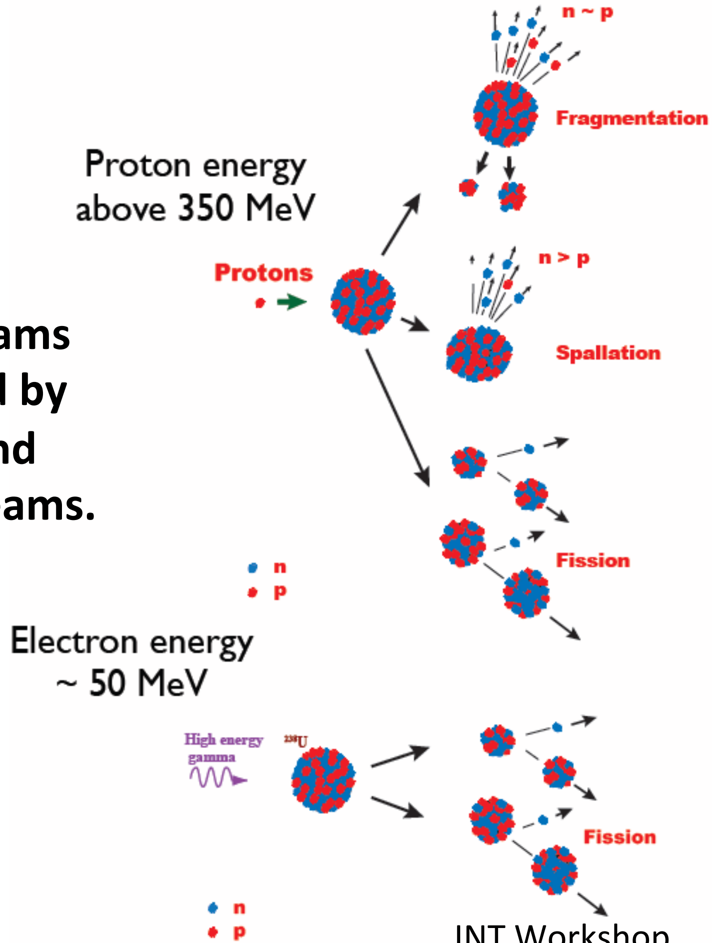
ARIEL Project:

- new electron linac driver for photo-fission
- new target stations and front end
- new proton beamline

E-linac and electron beamline
Sept. 2014

ARIEL photo-fission beams

Rare-isotope beams will be produced by from proton and electron driver beams.



500MeV Protons on UCx

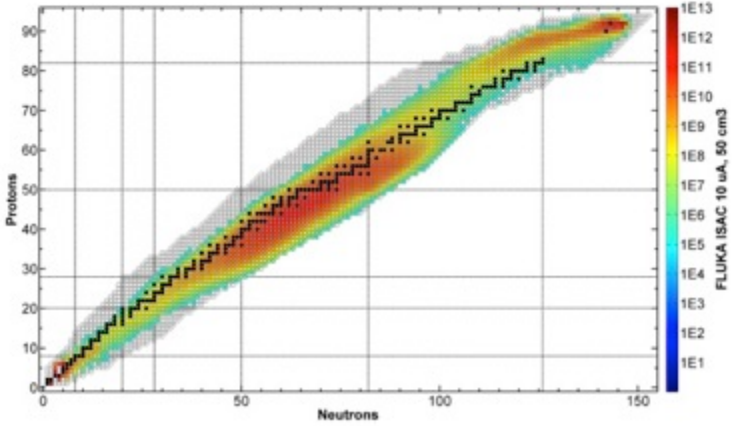
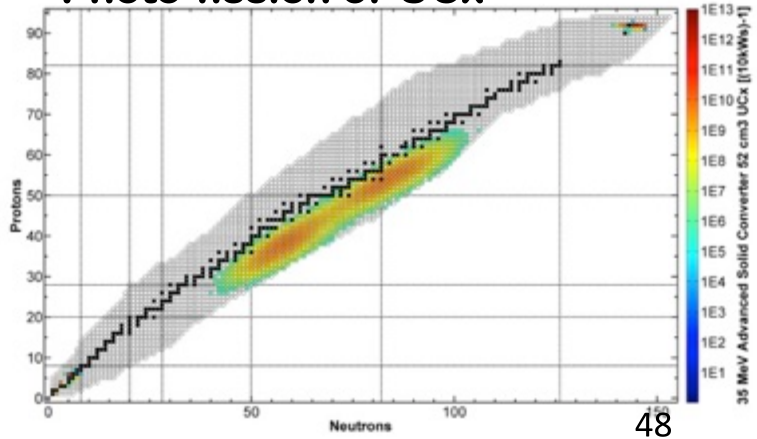


Photo-fission of UCx



The goal of ARIEL: science and opportunities

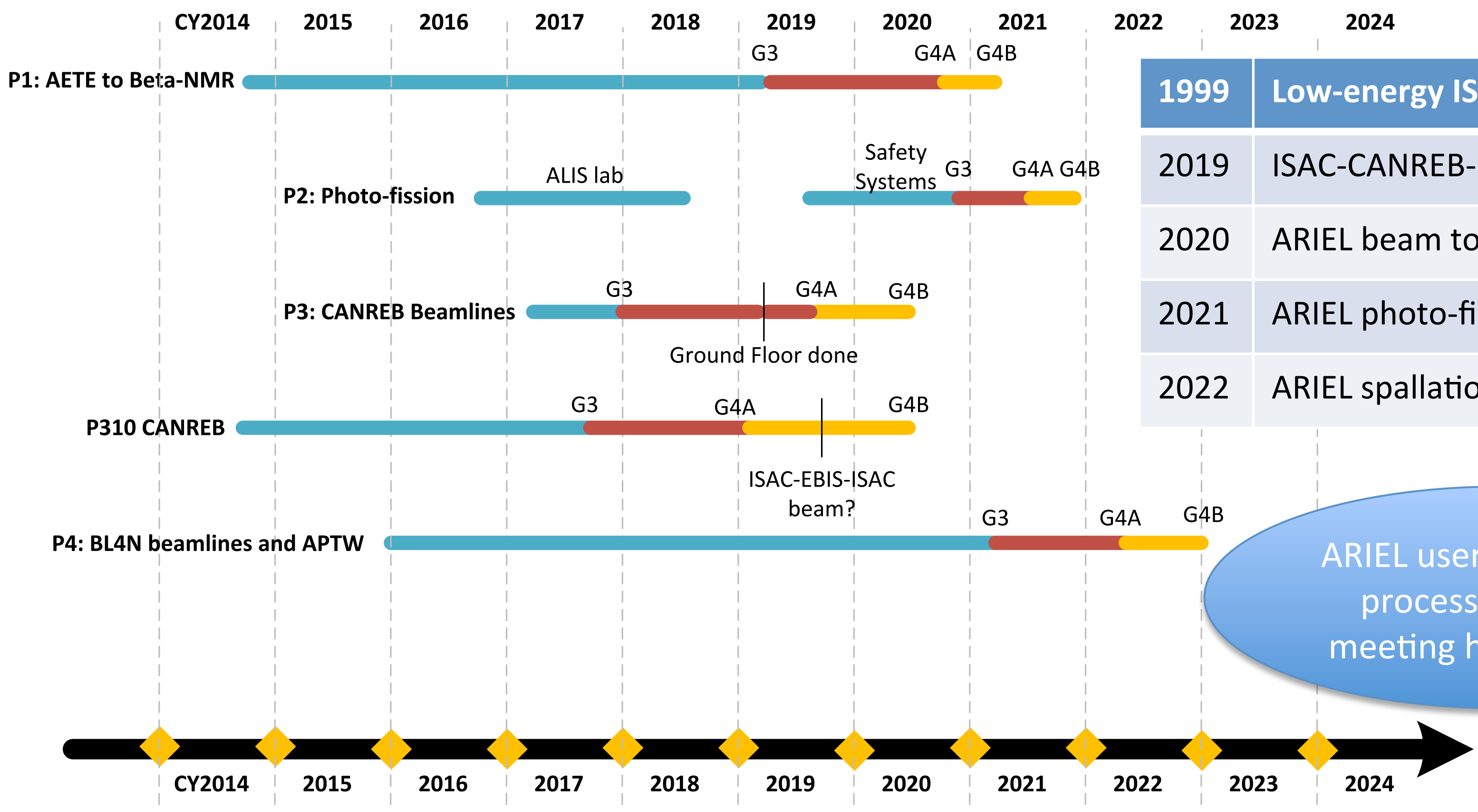
ISOTOPES

- **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**

ARIEL Completion to Science



1999	Low-energy ISAC beams
2019	ISAC-CANREB-ISAC beams
2020	ARIEL beam to β-NMR
2021	ARIEL photo-fission beams to ISAC
2022	ARIEL spallation beams to ISAC

ARIEL user consultation process: town-hall meeting held Jan 2017

TRIUMF

Canada’s national laboratory for particle and nuclear physics

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

TRIUMF: Alberta | British Columbia | Calgary | Carleton | Guelph | McGill | Manitoba | McMaster | Montréal | Northern British Columbia | Queen’s | Regina | Saint Mary’s | Simon Fraser | Toronto | Victoria | Western | Winnipeg | York

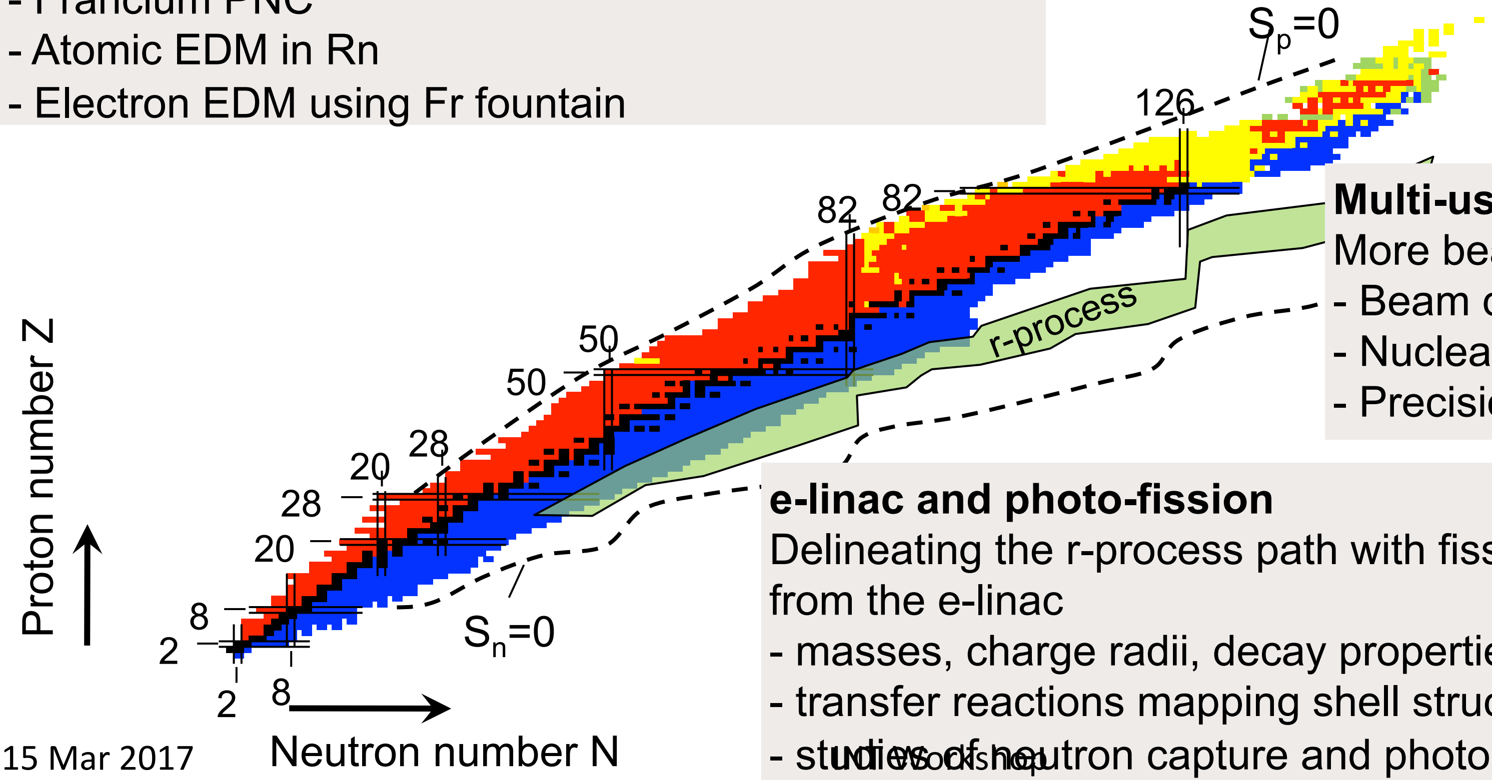
Thank you!
Merci!

Follow us at TRIUMFLab

The Future: Science enabled by ARIEL

Actinide proton beam-line:
High intensity, clean beams for electroweak precision experiments using hundreds of days of beam per year
- Francium PNC
- Atomic EDM in Rn
- Electron EDM using Fr fountain

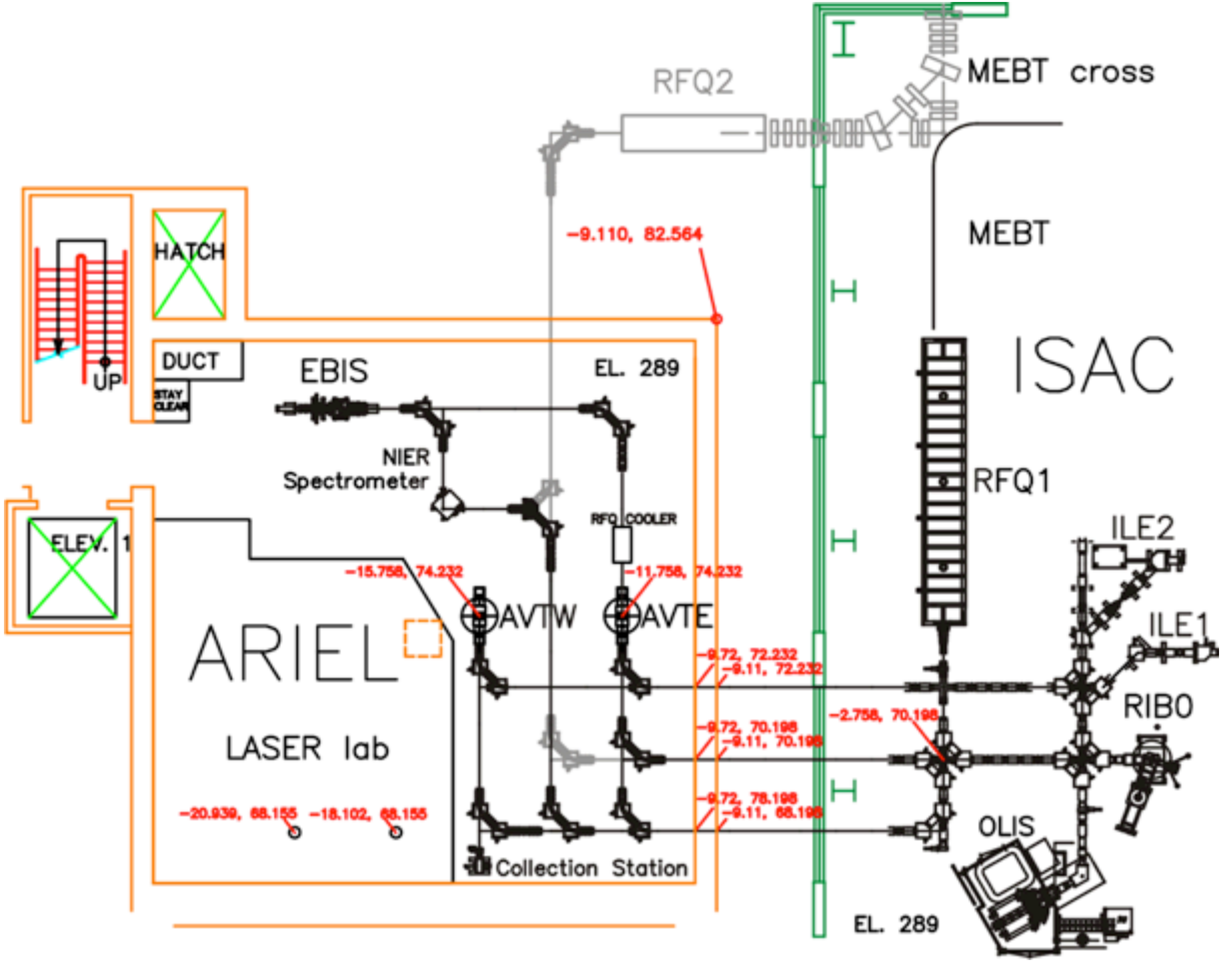
TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY



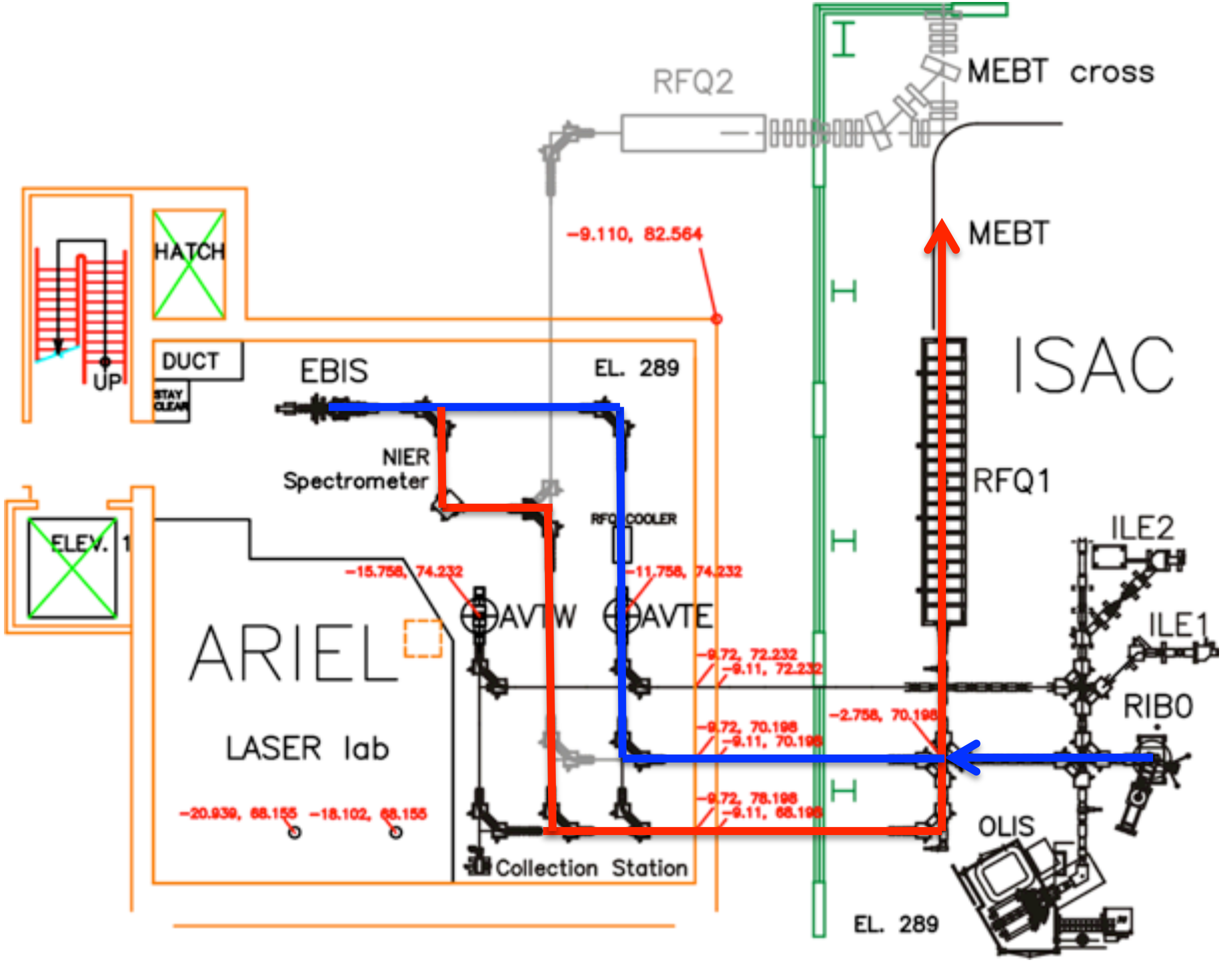
Multi-user operations:
More beam time for
- Beam development
- Nuclear astrophysics
- Precision experiments

e-linac and photo-fission
Delineating the r-process path with fission fragment beams from the e-linac
- masses, charge radii, decay properties
- transfer reactions mapping shell structure
- studies of neutron capture and photo dissociation rates

Charge-breeding ISAC beams with ARIEL-CANREB EBIS



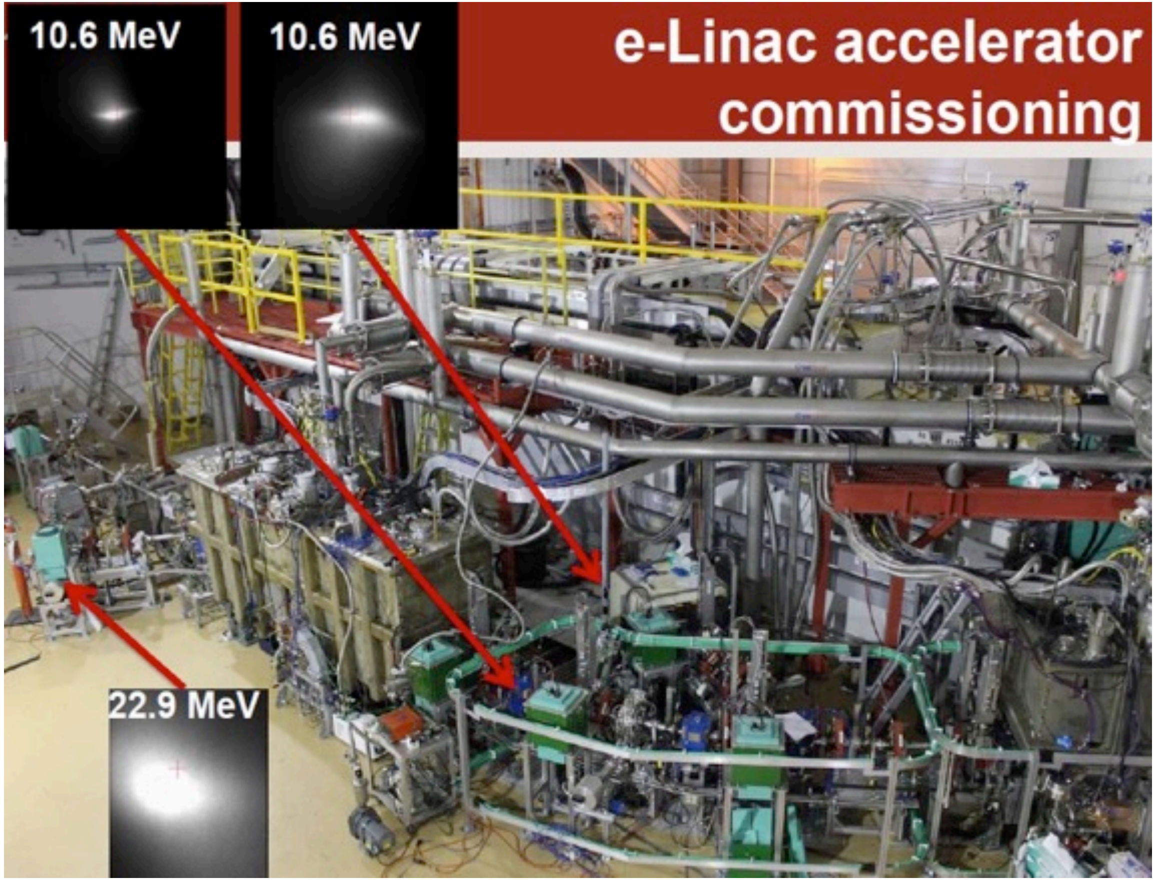
Charge-breeding ISAC beams with ARIEL-CANREB EBIS

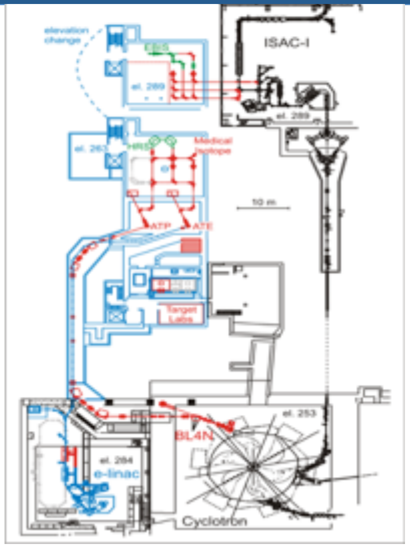


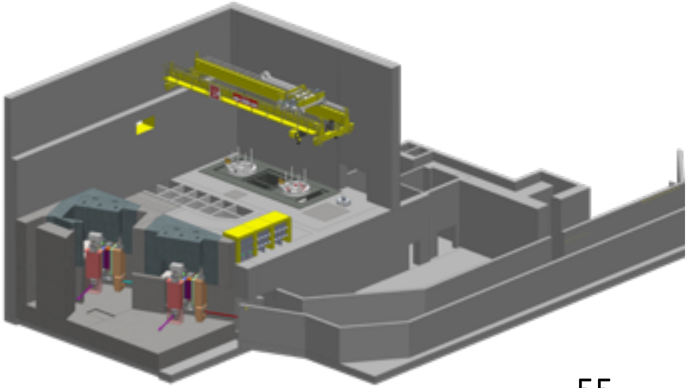
Singly-charge RIB

Highly-charged RIB

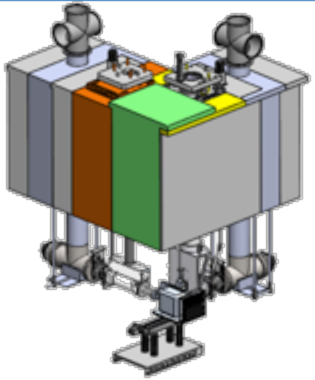
ARIEL-1: e-linac completed and commissioned



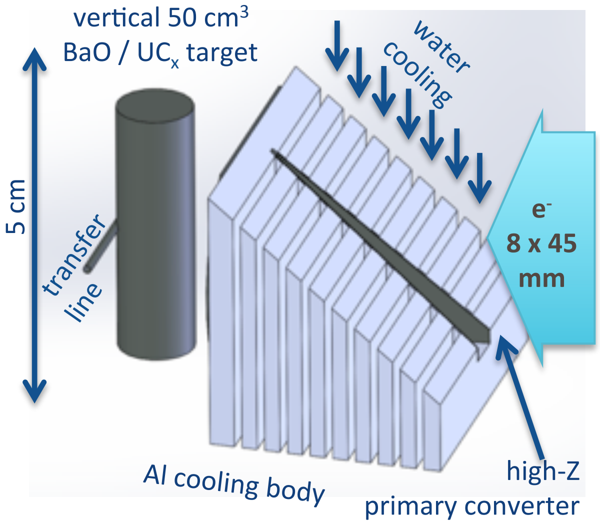


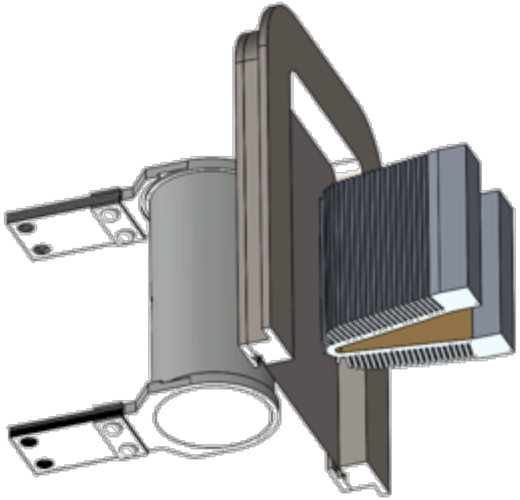


ARIEL-2: developments



- Target developments for p- and γ-fission targets with $^{238}UC_x$ (100kW)
- New target removal and exchange concept (internat. review)
- Test stand for e-hall





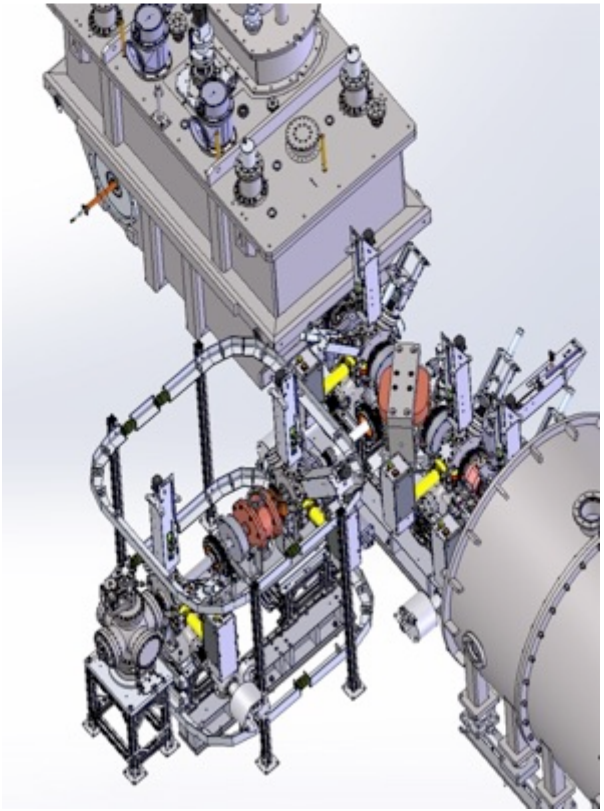


Photo-fission isotopes

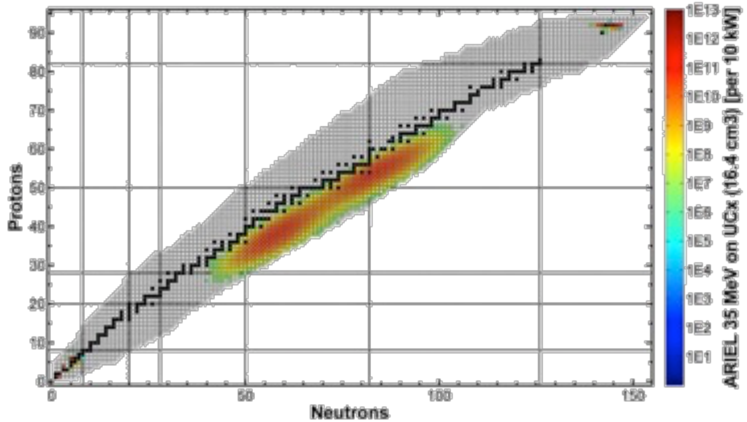
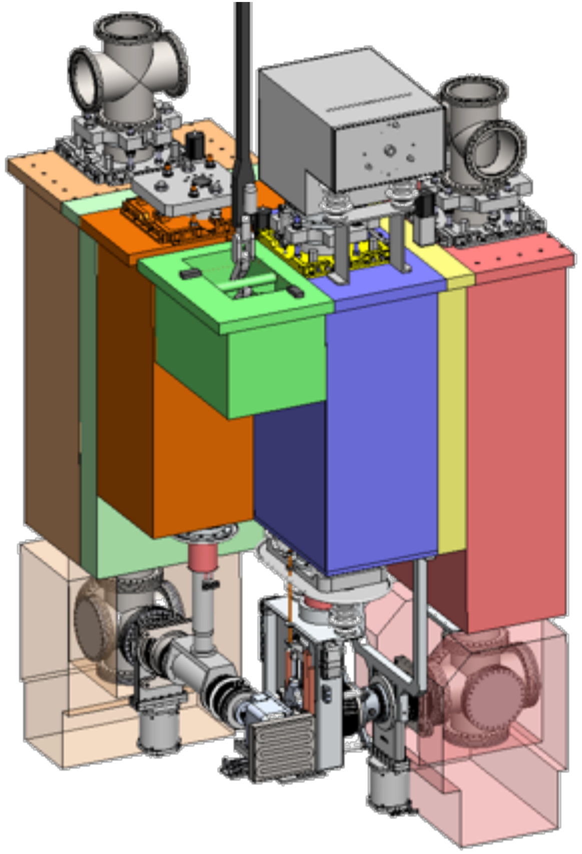


Photo-fission isotopes:

- ‘cleaner’ n-rich isotopes
- Limited to 100kW targets initially (10^{12} fission)
- Can be achieved with conventional technologies

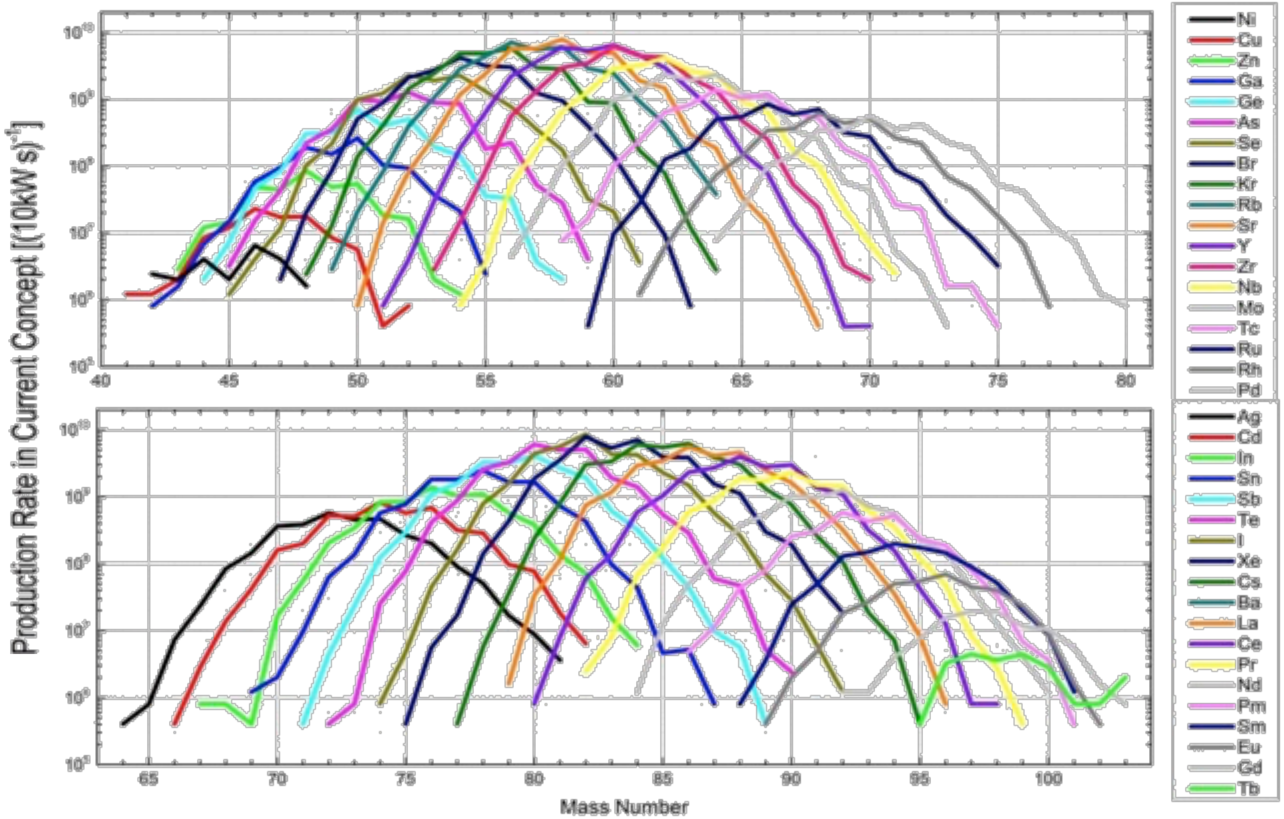
- Factory model for three beams developed
  - Target exchanges every 3 weeks
  - Storage of targets for up to 3 years
  - New target production capabilities



Modular target system, hermetically sealed units

FLUKA Production Map from 35 MeV Electrons

ARIEL Current Concept Design In-Target Production Yields [10 $kW^{-1} \cdot s^{-1}$]



In-target production rates [10 $kW^{-1} \cdot s^{-1}$]:

from BeO:

^{8}Li: $5 \cdot 10^{10}$

from UC_x:

^{78}Ni: $1 \cdot 10^{5}$

^{98}Kr: $8 \cdot 10^{7}$

^{100}Rb: $1 \cdot 10^{8}$

^{98}Sr: $5 \cdot 10^{9}$

^{132}Sn: $5 \cdot 10^{8}$

^{146}Xe: $2 \cdot 10^{7}$

^{144}Ba: $5 \cdot 10^{9}$

^{150}Cs: $4 \cdot 10^{5}$

500MeV Protons on UC_x:

^{78}Ni: $2 \cdot 10^{6}$

^{98}Kr: $1 \cdot 10^{8}$

^{100}Rb: $9 \cdot 10^{7}$

^{98}Sr: $1 \cdot 10^{10}$

^{132}Sn: $5 \cdot 10^{9}$

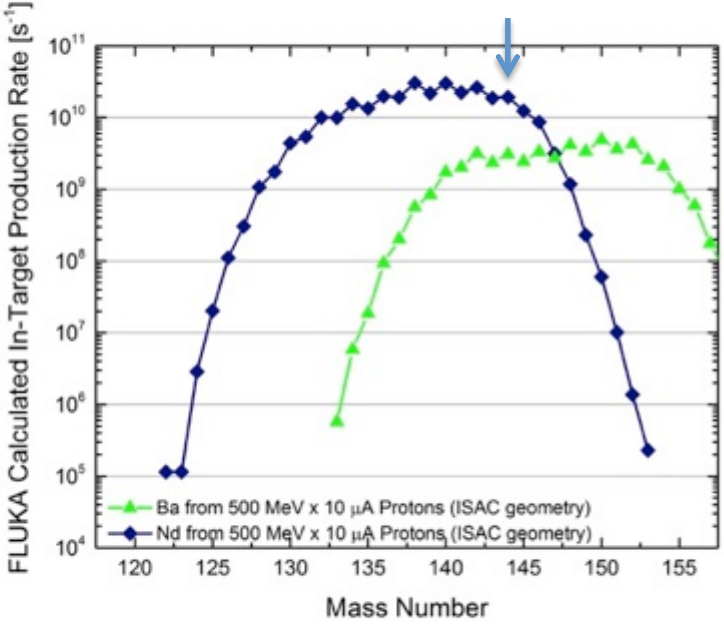
^{146}Xe: $1 \cdot 10^{7}$

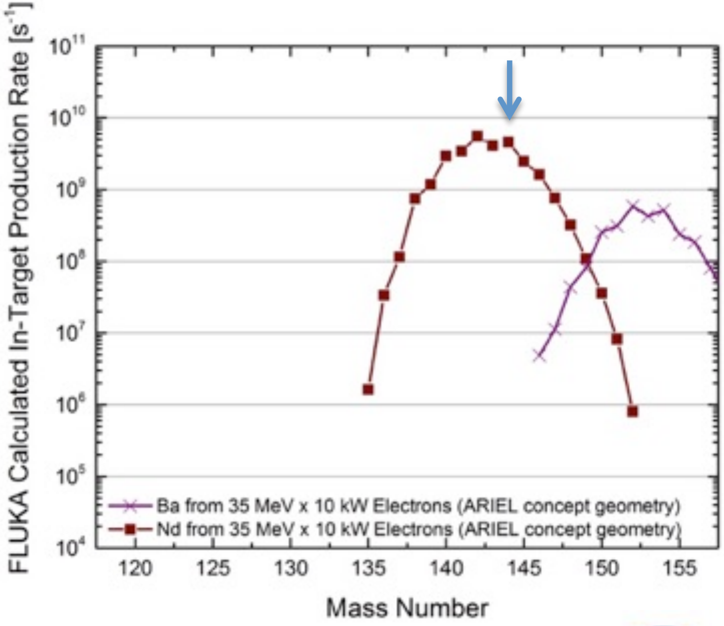
^{144}Ba: $2 \cdot 10^{10}$

^{150}Cs: $5 \cdot 10^{5}$

FLUKA: A. Gottberg (TRIUMF and results verified independently with GEANT4 (Maria Cervantes Smith, University of Victoria)

ARIEL photo-fission beams to ISAC





^{144}Ba is doubly-magic for octupole deformation; *Z*=56, *N*=88.

500MeV protons: $2x10^{10}$ with $3x10^{9}$ Nd (and Ce, Pr, Pm, Sm, Eu, Gd etc)

10kW electrons: $5x10^{9}$ with zero Nd