A Decade of Radioactive Beams at ISAC

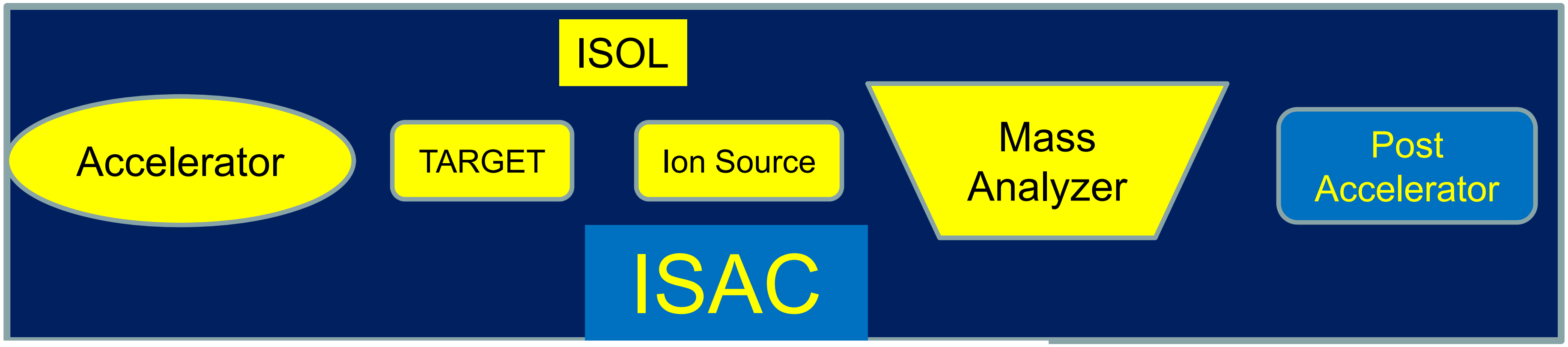
Reflecting on ISAC’s 10 Year History

First Beam (^{36m}K) – November 1998

John M. D’Auria
Simon Fraser University

- What is ISAC?
- What is its place in the World?
- How Did It Start?
- Science in the First 10 Years?
- What Does the Future Hold?
- Concluding Remarks?

What is ISAC?



ISOL

Accelerator

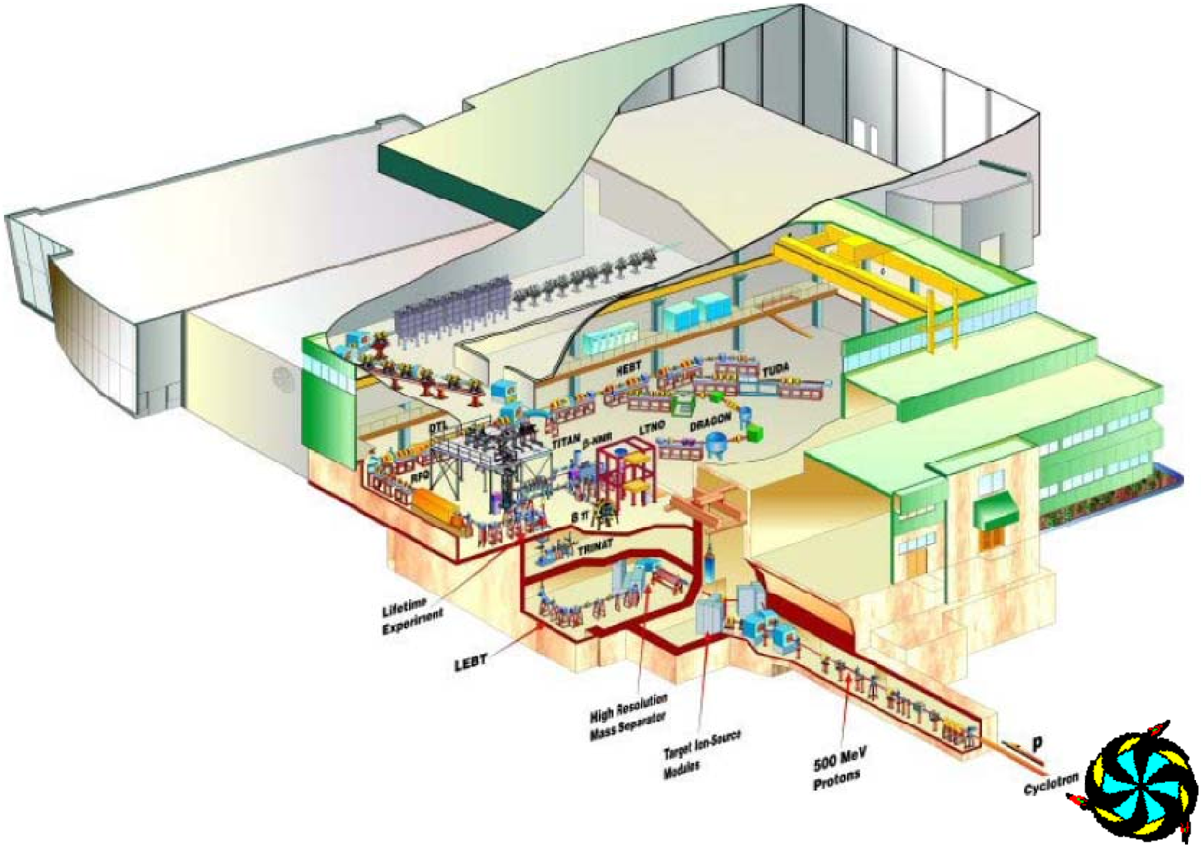
TARGET

Ion Source

Mass Analyzer

Post Accelerator

ISAC



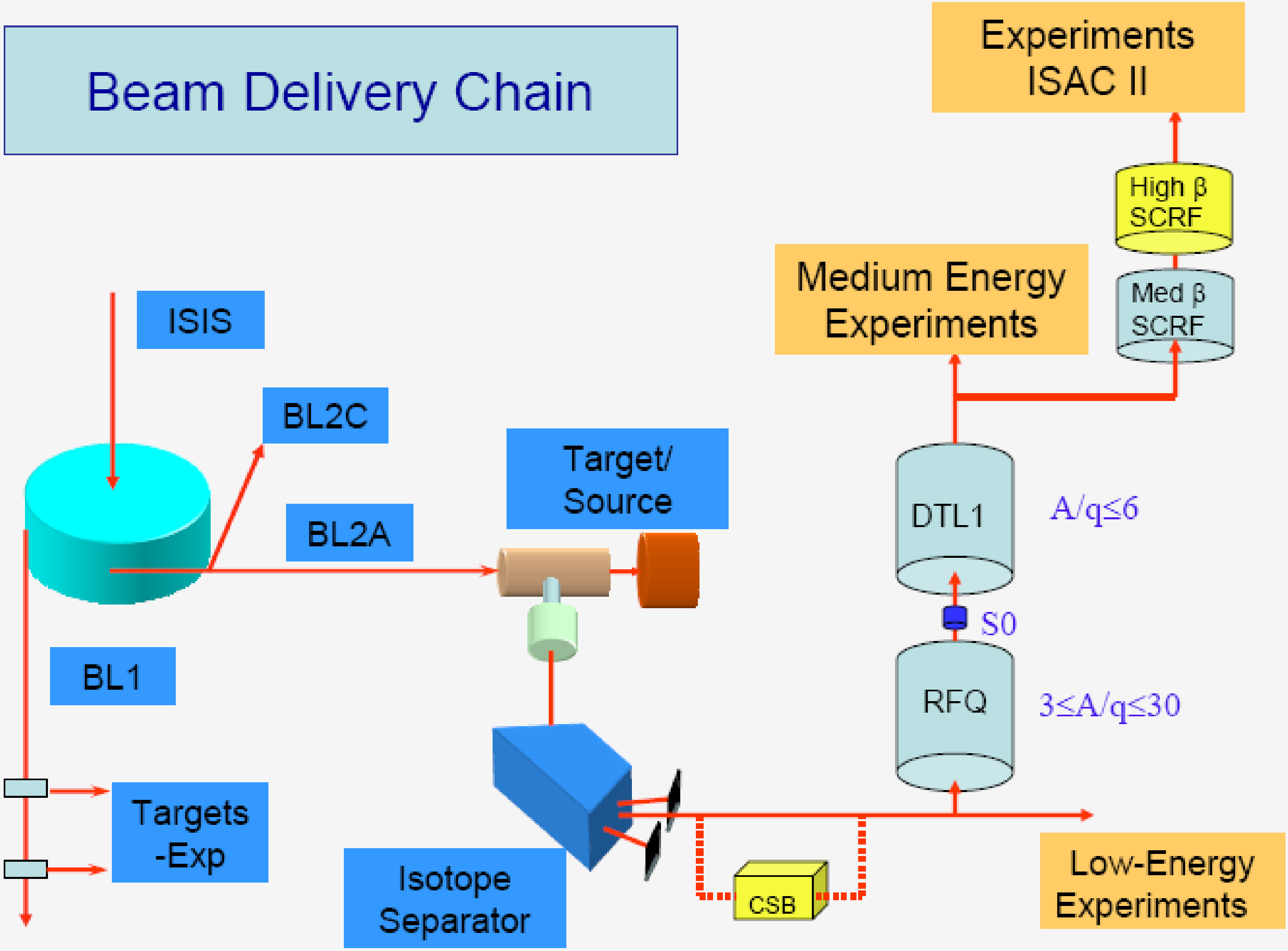
Latest generation of an on-line isotope separator (ISOL)

Elemental selectivity based upon the Target and Ion Source; Mass selectivity based upon Mass Analyzer

Chemistry and Physics

Coupling of an ISOL with a post-accelerator to produce energetic RB (essentially the first in the world)

Beam Delivery Chain



Experiments
ISAC II

High β
SCRF

Medium Energy
Experiments

Med β
SCRF

ISIS

BL2C

Target/
Source

BL2A

DTL1

A/q≤6

S0

BL1

RFQ

3≤A/q≤30

Targets
-Exp

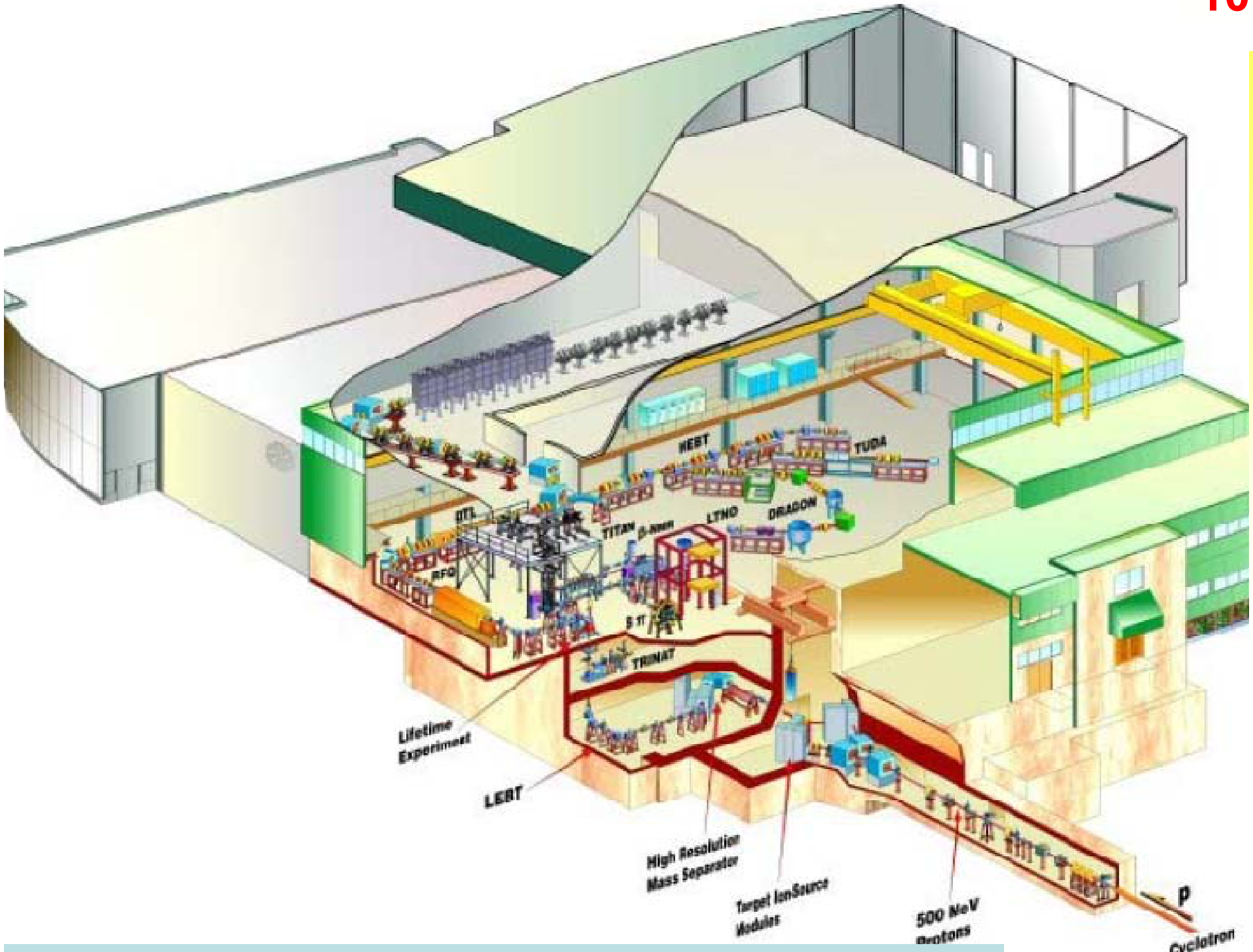
Isotope
Separator

CSB

Low-Energy
Experiments

ISAC @ TRIUMF

ISAC:
Highest power for On-Line facilities, presently up to 100μA @ 500MeV DC proton



ISAC has 3 exper. areas:

- **Low energy (< 60keV)**
- **ISAC I (150 keV/u –1.8 MeV/u)**
- **ISAC II (up to 16MeV/u, presently being upgraded)**

Suite of experimental stations:

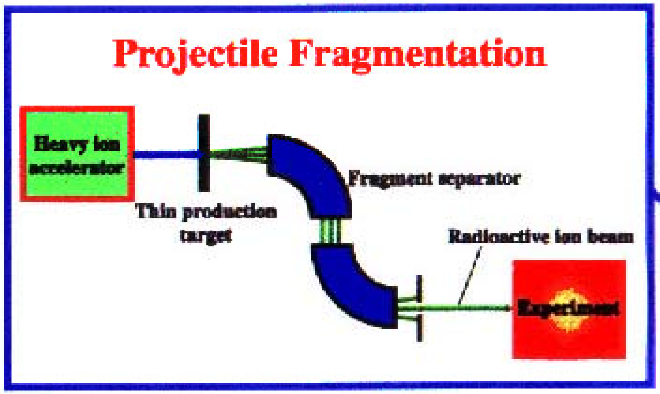
- **TRINAT, Beta-NMR, 8pi, tape-station, TITAN, Co-linear laser spec, polarised beam line, etc**
- **DRAGON, TUDA, TACTIC, GPS,**
- **TIGRESS (8/12),**
- **EMMA (2011),**
- **HERACLES**

Some Beam Intensities @ Yield Station

^{8}Li	(Ta)	8 x 10^{8} pps
^{11}Li	(Ta)	4 x 10^{4} pps
^{21}Na	(SiC)	9.9 x 10^{9} pps
^{26g}Al	(SiC)	1 x 10^{10} pps
^{74}Rb	(Nb)	1.3 x 10^{4} pps
^{79}Rb	(Nb)	4.6 x 10^{9} pps
^{160}Yb	(Ta)	8.4 x 10^{9} pps

Target material for beam production includes SiC, CaO, TiC, U (UO and UC license)
Ion sources: surface, laser, FEBIAD, ECR (test)

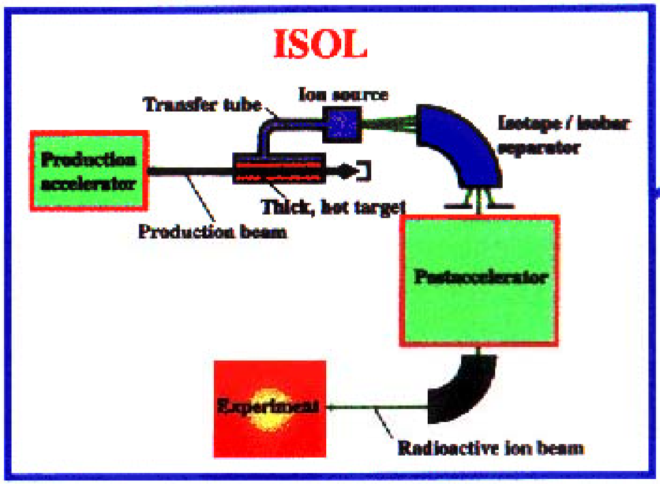
World of Radioactive Beams Facilities



In-Flight Fragmentation
(heavy ion energetic beams)

- **NSCL (MSU) → FRIB (~$500M)**
- **GSI (Germany) → FAIR (~$1 B)**
- **RIKEN (Japan)**
- **GANIL (France)**

ISAC



ISOL Method
(2 accelerators)
ISOLDE (Cern)→ HIE-ISOLDE ?
ISAC (Canada) → ISAC II →
HRIBF (ORNL) → ??
SPIRAL (France) →SPIRAL 2 ?
Louvain (Belgium)→LISOL+ ??

Other Approaches
Jyvaskala (Finland)
UND, TAMU,…CARIBU (ANL) ?

ISAC presently produces highest intensity RB in world (for selected beams)

How did it start?

(Pre-ISAC Highlights)

- 1951 First on-line ISOL (Niels Bohr Inst.)
- 1969–present ISOLDE (CERN)
- ‘60-80’s- Various ISOL facilities (OSIRIS, ISOCEL, TRISTAN, UNISOR, …)
- ~1970’s – John Warren suggests an ISOL on BL1;
- ~1980’s – Proposal to move TRISTAN to BL4A
- 1985 – Proposal to TRIUMF BOM

  Conferences at Mount Gabriel and Parksville
- 1986–1999 TISOL (R&D and Production RB facility)

  (Mini Workshops at Lake Harrison (WEISS), and Lake Louise
- 1995 – ISAC Funding (and Construction starts)
- 1998 – First beam (^{38m}K) to TRINAT

1951: First ISOL beams at NBI

O. K Hansen and K.O. Nielsen

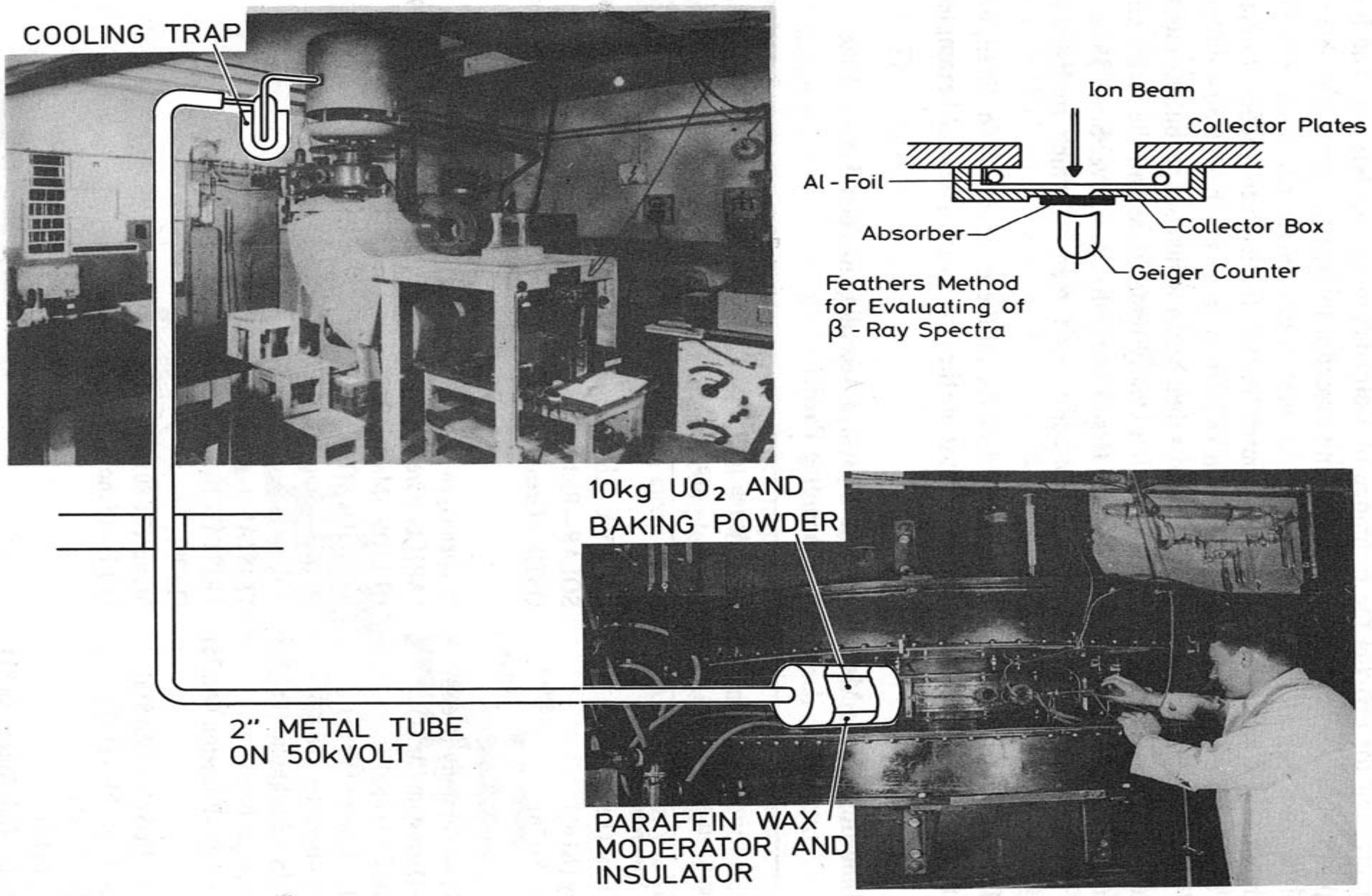


Figure 3. The Copenhagen isotope separator.

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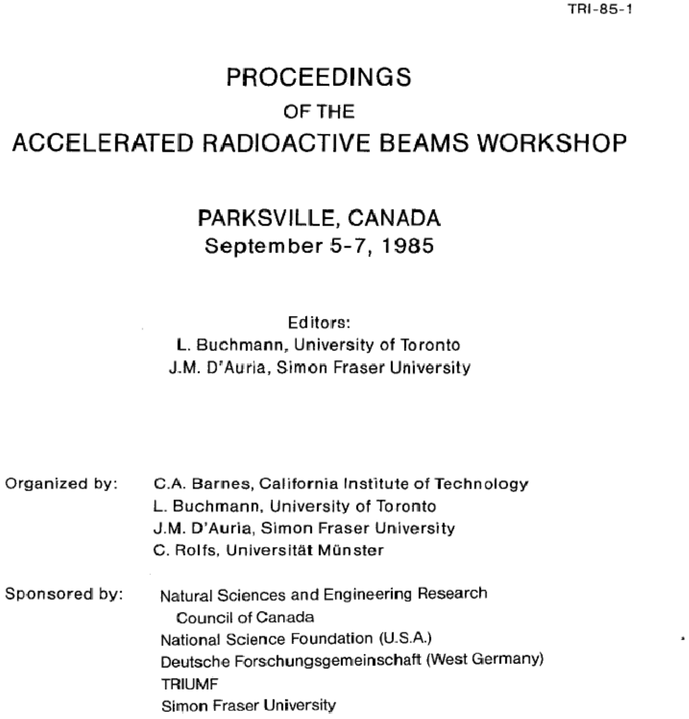
TRIUMF

PROCEEDINGS
OF THE
TRIUMF-ISOL WORKSHOP

MONT GABRIEL, QUÉBEC
JUNE 13-16, 1984

Editors:
J. Crawford, McGill University
J.M. D'Auria, Simon Fraser University

1984



TRI-85-1

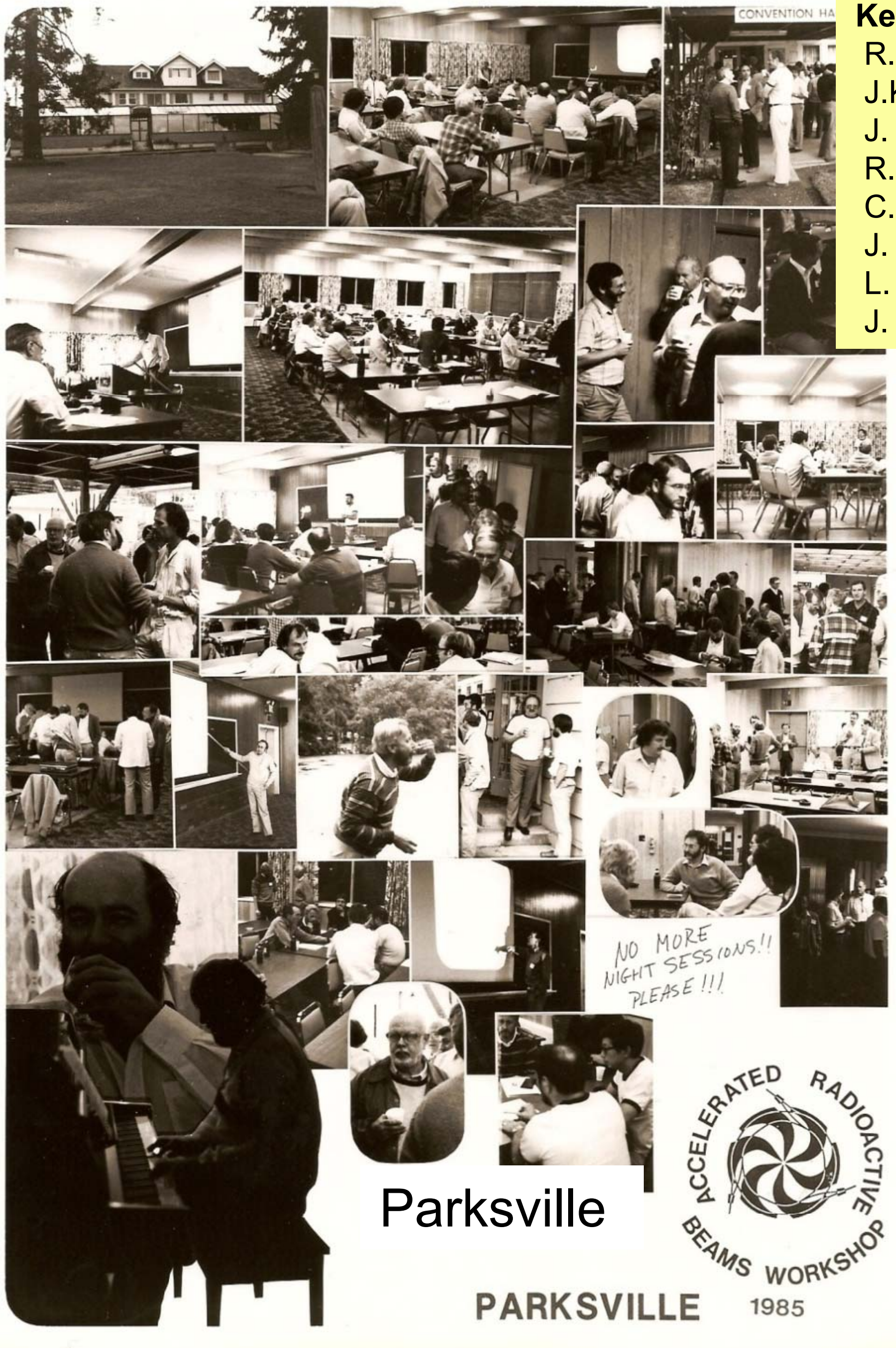
PROCEEDINGS
OF THE
ACCELERATED RADIOACTIVE BEAMS WORKSHOP

PARKSVILLE, CANADA
September 5-7, 1985

Editors:
L. Buchmann, University of Toronto
J.M. D'Auria, Simon Fraser University

Organized by:
C.A. Barnes, California Institute of Technology
L. Buchmann, University of Toronto
J.M. D'Auria, Simon Fraser University
C. Rolfs, Universität Münster

Sponsored by:
Natural Sciences and Engineering Research Council of Canada
National Science Foundation (U.S.A.)
Deutsche Forschungsgemeinschaft (West Germany)
TRIUMF
Simon Fraser University



Parksville

Key Players:
- R. Azuma-UToronto
- J.K.P. Lee McGill
- J. Crawford, McGill
- R. Moore, McGill
- C. Rolfs, Munster
- J. King, UToronto
- L. Buchmann, UT
- J. D'Auria, SFU

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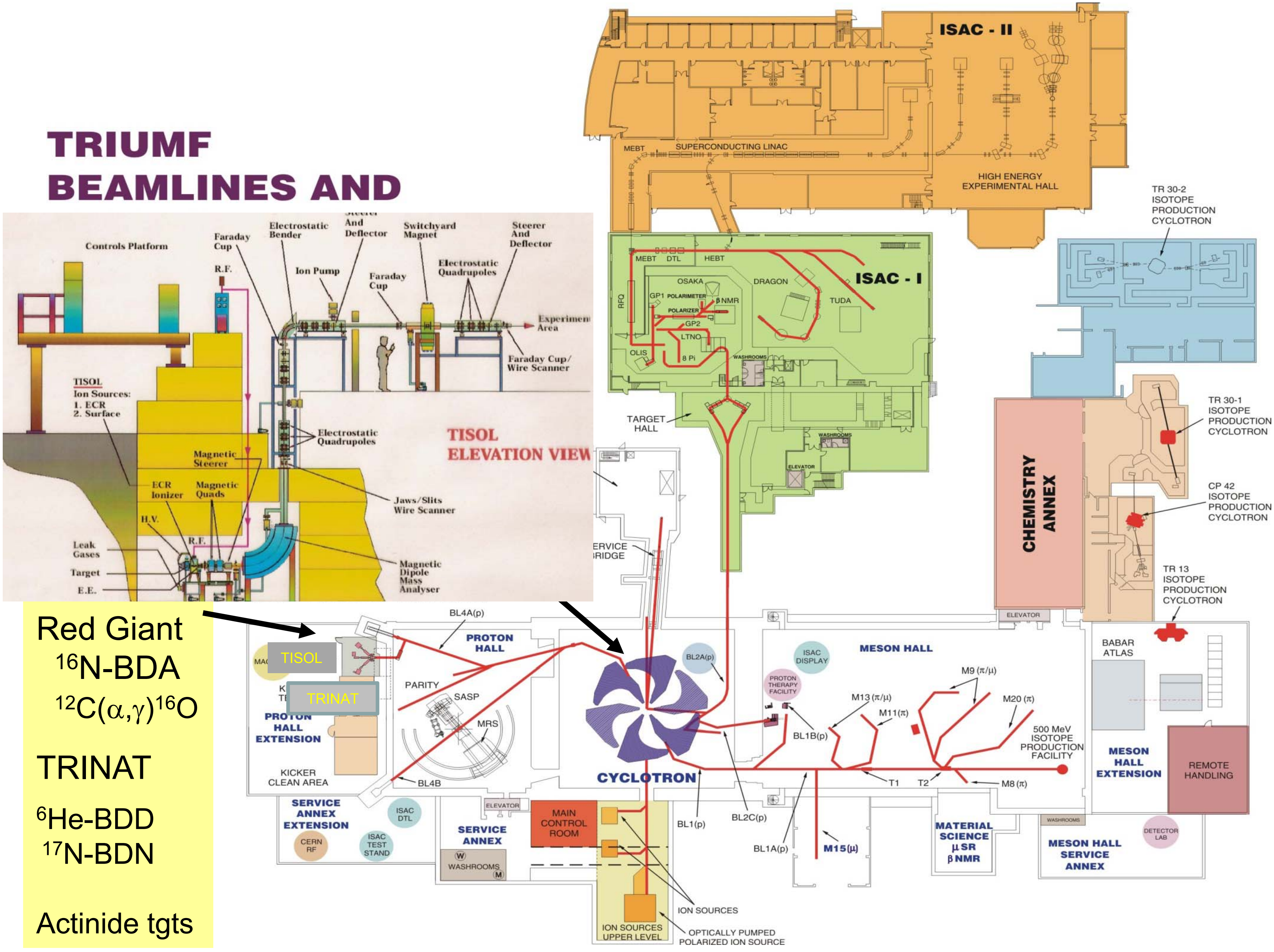
TRIUMF BEAMLINES AND



Red Giant
^{16}N-BDA
^{12}C(α,γ)^{16}O

TRINAT

^{6}He-BDD
^{17}N-BDN

Actinide tgts

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ISAC
Isotope Separator/Accelerator

ISAC will accelerate radioactive isotopes to high velocities, a capability which will allow scientists to replicate reactions which occur in stars in the distant universe, and to study nuclear structure, the behavior of unusual atomic nuclei, condensed matter physics and life sciences projects. This is recognized worldwide as leading edge research and will place Canada back in the forefront of nuclear physics. The world physics community wanted ISAC, and Canada was in a unique position to develop it because TRIUMF can use the high power proton beam from the existing TRIUMF cyclotron to produce the copious beams of exotic, short-lived radioisotopes needed for the ISAC facility.

1 ISAC ground breaking, April 1996
2 Installing first shielding in the target hall
3 Aerial view of TRIUMF
4 ISAC building from the southeast
5 Early construction phase of the target hall
6 Beam line 2A transports the proton beam from the TRIUMF cyclotron to the target in the new ISAC facility
7 Installing the Radio Frequency Quadrupole tank
8 Tunnel construction from the cyclotron to the ISAC Facility
9 Completed ISAC building, February 1998

ISAC
Technical Highlights

(First 10 Years since First Beam)

Major Milestone

(ignoring infrastructure construction)

1998*** – First RB beam (^{38m}K) to TRINAT;

1998/9 – LEBT from OLIS to RFQ; RFQ full power

2000 – First physics (^{74}Rb lifetime with high precision)

(R. Boyd experiment??)

2001 – Accelerated beam of ^{21}Na to TUDA and DRAGON

2003 – TITAN and TIGRESS Funded; ISAC II bldg. opened

2004 – Laser ion source used for exp.; CSB tested;^{26g}Al beam found;
high power target developed

2005 – ^{4}He beam in single ISAC II module

2006 – ^{40} Ca beam accelerated to 5.5 MeV/u in ISAC II

2007 – Energetic ^{11}Li beam delivered to Maya Experiment in ISAC II

*** Remember funding in 1995 (built on budget and on schedule)

Challenges and Achievements

- RFQ LINAC (Room temperature, low frequency, 150 keV – 1.8 MeV/u)
- High power targets (Handling up to 5 kWatts)
- Thin ISOL targets to allow fast release of very short isotopes
- Selection of ion sources (surface, FEBIAD, LASER, ECR?)
- Unique shielding and remote handling (using cranes not robots)
- Professional Operations (as compared to older ISOL facilities)
- Proper Remote Control Systems (EPICS based)
- Excellent collection of world class, experimental facilities
- Fixed beam scheduling (Unlike HRIBF, NSCL, others?)
- OLIS (almost forgotten initially)

Scientific Highlights

(First 10 Years)

Science at ISAC

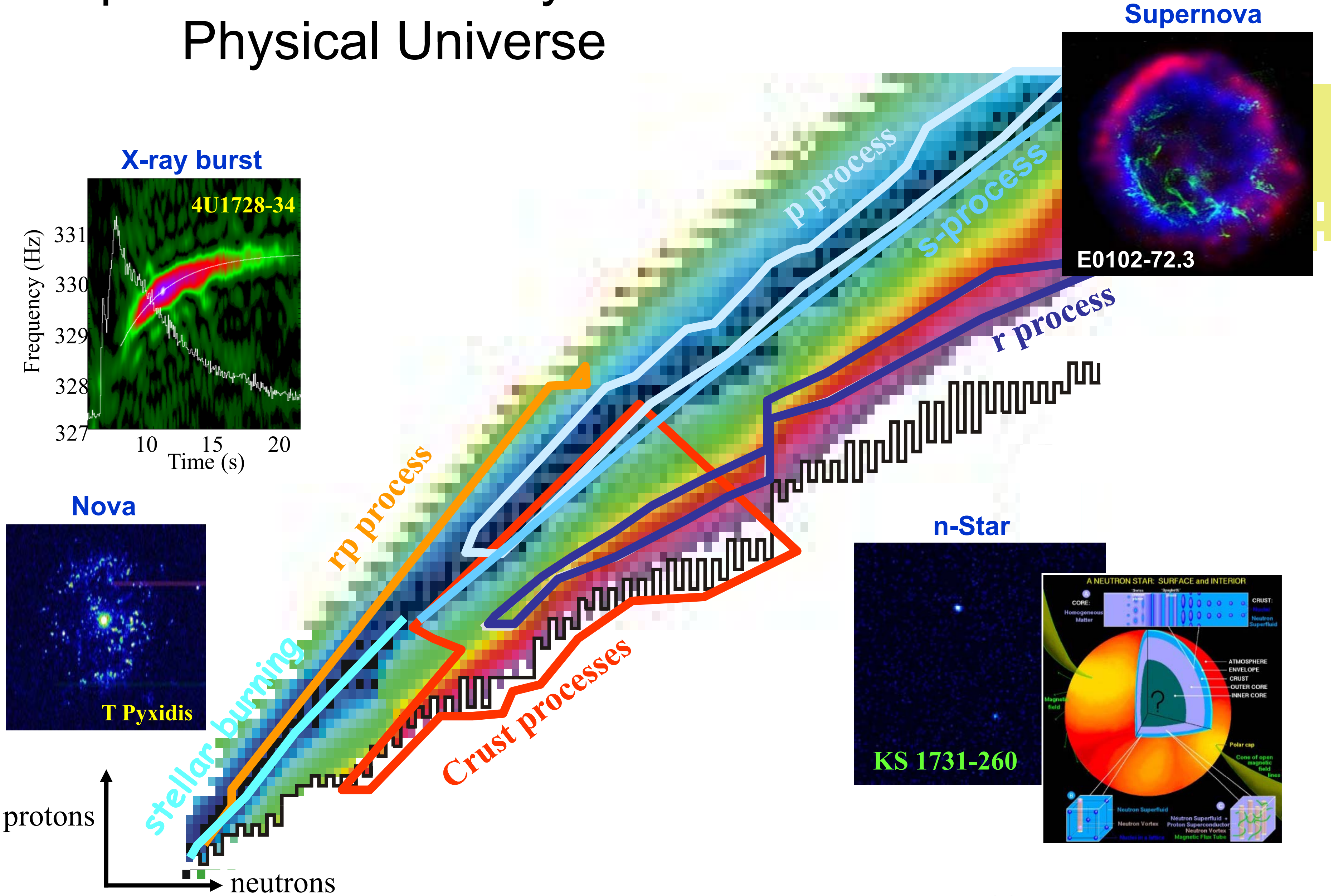
The First 10 Years

- Nuclear Astrophysics
  - DRAGON
  - TUDA
  - DAT
- Fundamental Physics
  - TRINAT
  - Precision Lifetime Measurements
- Condensed Matter Physics
  - Beta NMR and Polarized ^{8}Li
  - low field beta-NMR and zero field beta-NQR
- Nuclear Structure
  - The 8π (and peripheral detector arrays)
  - TIGRESS
  - Halo Nuclei Experiments
  - MAYA experiment
- Nuclear Masses
  - TITAN (CPT??)

Nuclear Astrophysics

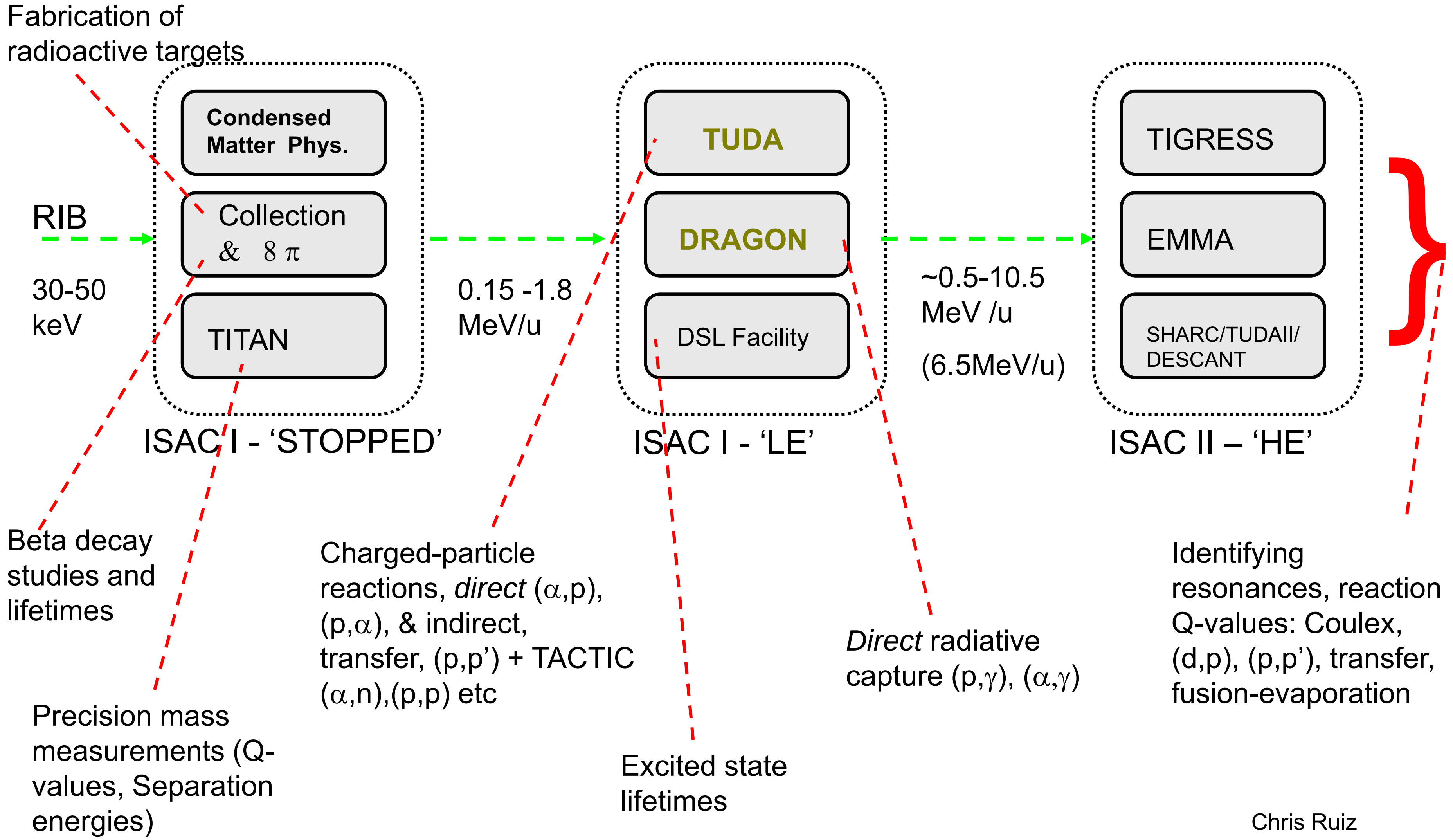
DRAGON
TUDA
DTM

Impact of Nuclear Physics on Physical Universe



Thanks to Witek Nazarewicz, U. Tennessee/ Greg Hackman

ISAC - Poised to Measure Nuclear Astrophysics



Fabrication of radioactive targets

RIB

30-50 keV

Condensed Matter Phys.

Collection & 8 π

TITAN

ISAC I - ‘STOPPED’

0.15 -1.8 MeV/u

TUDA

DRAGON

DSL Facility

ISAC I - ‘LE’

~0.5-10.5 MeV /u

(6.5MeV/u)

TIGRESS

EMMA

SHARC/TUDAII/ DESCANT

ISAC II – ‘HE’

Beta decay studies and lifetimes

Precision mass measurements (Q-values, Separation energies)

Charged-particle reactions, *direct* (α,p), (p,α), & indirect, transfer, (p,p’) + TACTIC (α,n),(p,p) etc

Excited state lifetimes

Direct radiative capture (p,γ), (α,γ)

Identifying resonances, reaction Q-values: Coulex, (d,p), (p,p’), transfer, fusion-evaporation

Chris Ruiz

DRAGON

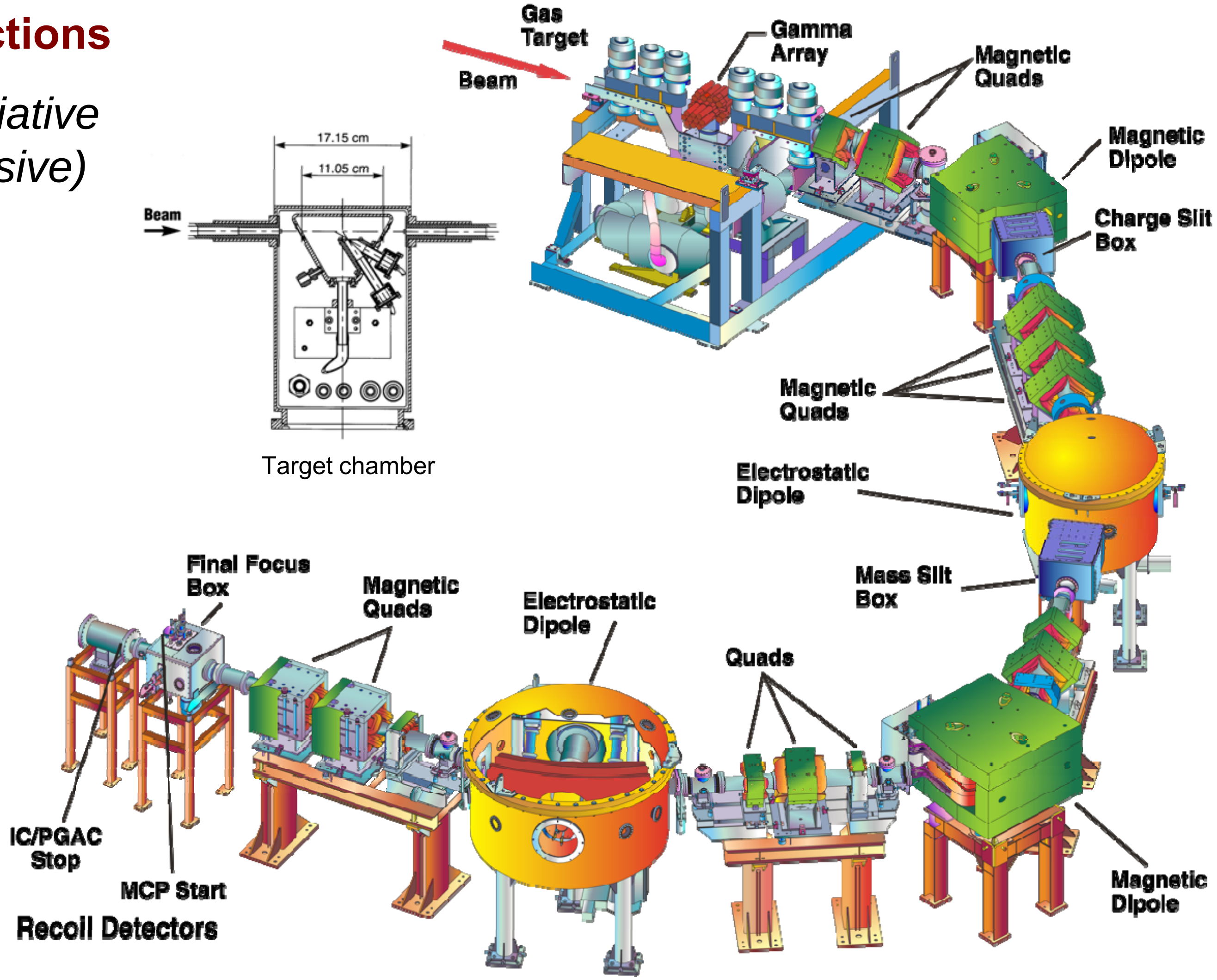
C. Ruiz

Detector of Recoils and Gammas of Nuclear Reactions

Direct measurement of radiative capture reactions at (explosive) stellar energies, in inverse kinematics

- MEME design
- Windowless recirculating target: H_2 or He
- LN2 zeolite cleaning trap
- 1-10 mbar
- 30-element BGO gamma array;40-70% efficiency

Combination of RB + RFQ + DRAGON is unique in world



Target chamber

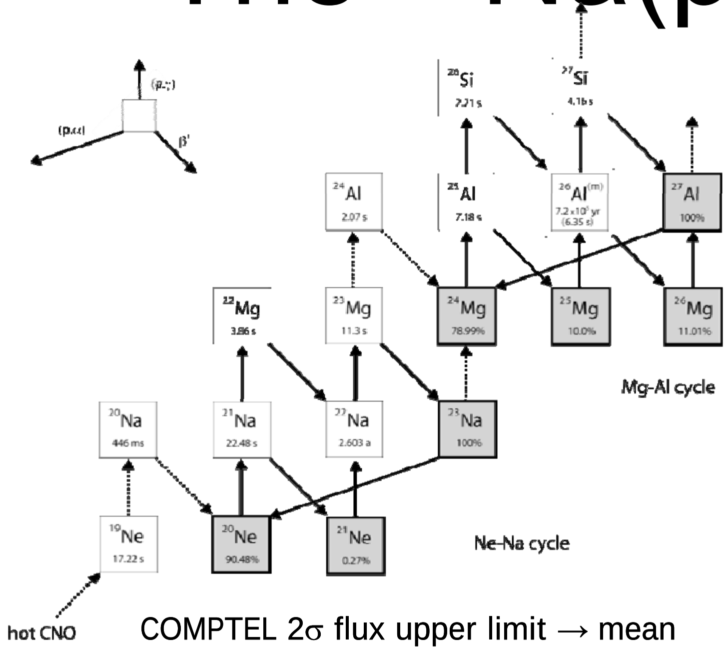
Large International Collaboration

DRAGON Program
Summary

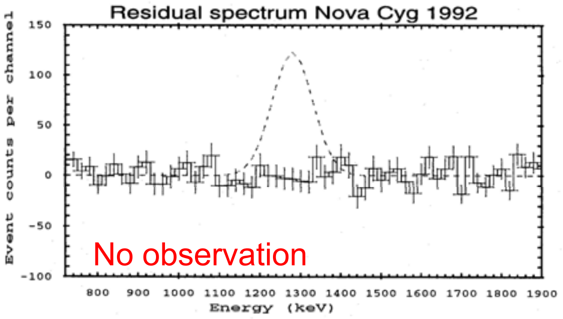
- 5 radiative capture reactions measured directly using RIBs in last 20 years (world).
  4 in last 8 years: 3 using DRAGON
- Textbook RIB measurement: ^{21}Na(p,γ)^{22}Mg for ^{22}Na synthesis in O-Ne novae
  All contributing resonances measured to high precision: reaction rate completely determined experimentally; *most intense (~10^9/s)* ^{21}Na RIB in world.
- *New* cascade transition in ^{12}C(α,γ)^{16}O
  DRAGON sensitive to transitions unobserved in other experiments
- *First inverse kinematics measurement* of ^{26g}Al(p,γ)^{27}Si, *highest intensity (~10^9/s)* ^{26g}Al beam in world
- Direct measurement of ^{40}Ca(α,γ)^{44}Ti in inverse kinematics for supernova ^{44}Ti production, *best measurement* so far
- *First direct measurement* of ^{23}Mg(p,γ)^{24}Al reaction using *most intense* ^{23}Mg RIB

- Production of Target of ^{22}Na to perform (p,γ) for ^{22}Na synthesis in O-Ne novae

The ^{21}Na(p,γ)^{22}Mg reaction



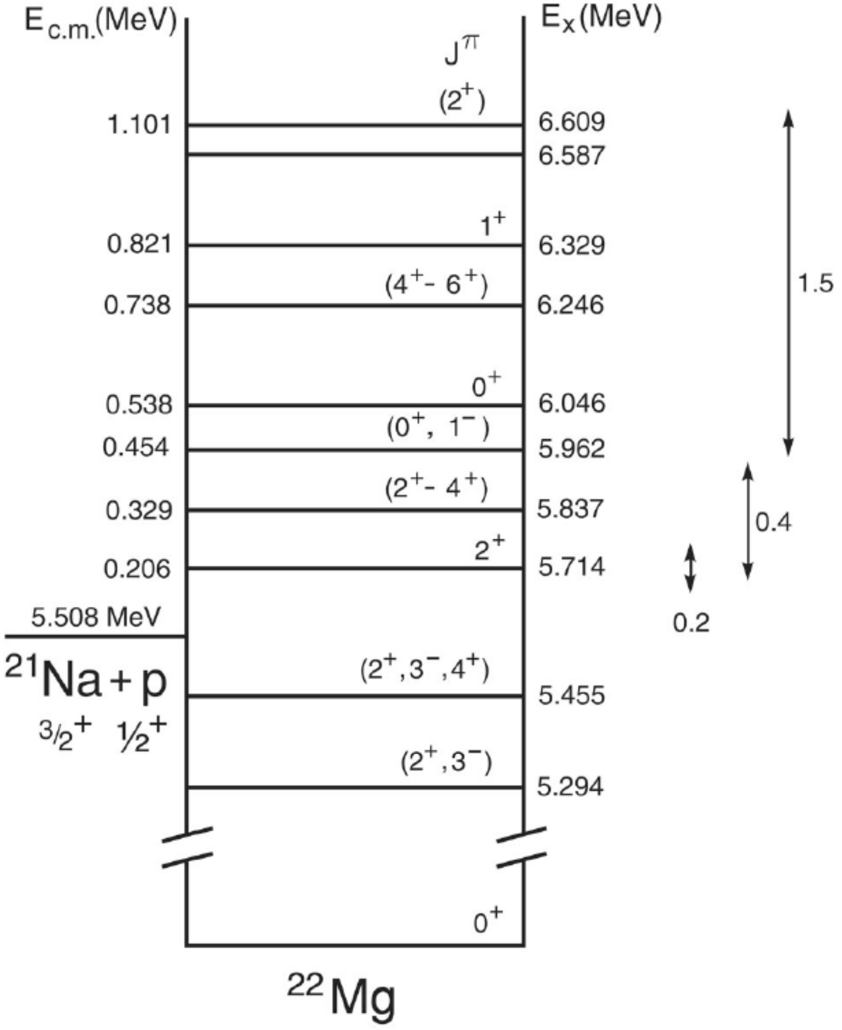
COMPTEL 2σ flux upper limit → mean yield $< 4 \times 10^{-8}$ $M_\odot$



A.F. Iyudin *et al*, Astron. Astrophys. **300**, 422 (1995)

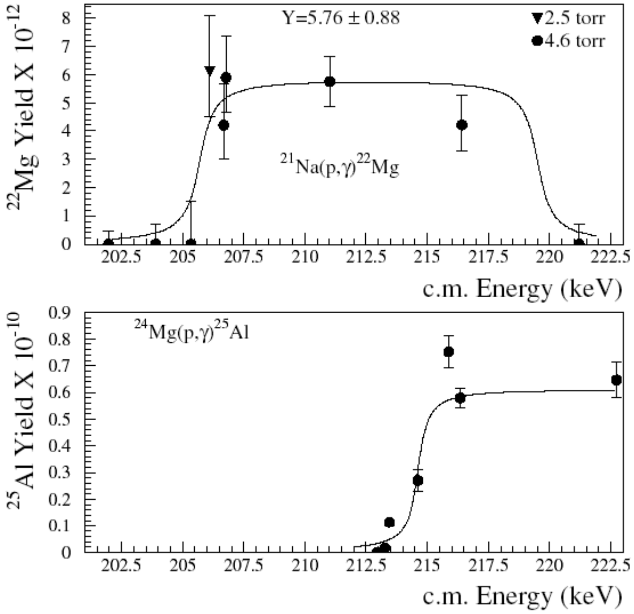
- 21Na(p,γ)^{22}Mg bypass for ^{21}Na(β^+)^{21}Ne(p,γ)^{22}Na route
- Stronger ^{21}Na(p,γ)^{22}Mg means ^{22}Na destroyed quicker
- Ejected ^{22}Na abundance strongly dependent
- Predicted abundance in O-Ne novae ~6 x 10^{-9} solar masses
- ^{22}Na: prospect of observation from single nearby (< 1kpc)* nova
- No observation by COMPTEL (Nova Her 1991 ~3kpc, Nova Cyg 1992 ~2kpc)
- INTEGRAL slightly more sensitive
- When observation comes, need accurate ^{22}Na ejected yield estimations

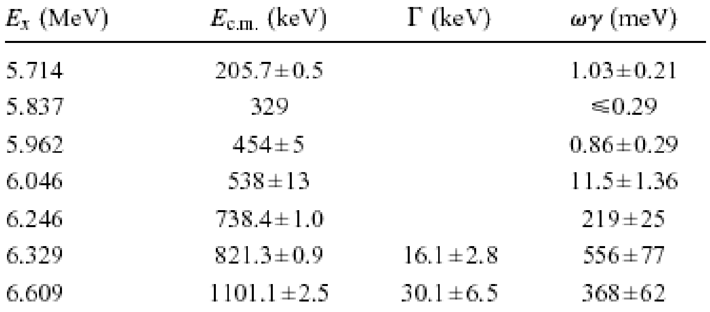
Level structure ^{22}Mg



RESULTS

Phys. Rev. Lett. 90, 16 (2003)
Phys. Rev. C 69, 065803 (2004)





E_x (MeV)	$E_{c.m.}$ (keV)	Γ (keV)	ωγ (meV)
5.714	205.7±0.5		1.03±0.21
5.837	329		≤0.29
5.962	454±5		0.86±0.29
6.046	538±13		11.5±1.36
6.246	738.4±1.0		219±25
6.329	821.3±0.9	16.1±2.8	556±77
6.609	1101.1±2.5	30.1±6.5	368±62

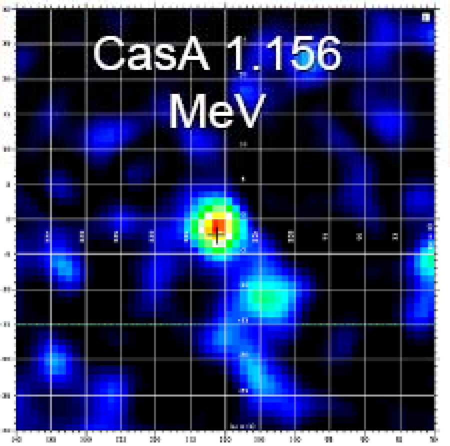
Conclusions on ^{21}Na(p,γ)^{22}Mg direct measurement

- ^{21}Na beam ‘easy’; prolific from spallation in SiC, readily ionizeable in rhenium
- Pure beam (no isobars)
- Primary beam radioactive and intense: normalization via elastic scattering and beta monitor sufficient
- Dominant experimental background: primary beam decay - shielding & high thresholds required
- High intensity makes thick target excitation functions possible in reasonable time
- Rate determined to +/- 20% precision
- ‘Classic’ DRAGON experiment

Spinoff: DRAGON measurement of E_R=206 keV ^{21}Na(p,γ)^{22}Mg resonance revealed a 6 keV discrepancy in the reaction Q-value, traced to the mass of ^{22}Mg

This has since been corroborated by re-evaluation: J. Hardy, Phys. Rev. Lett. 91 (2003)

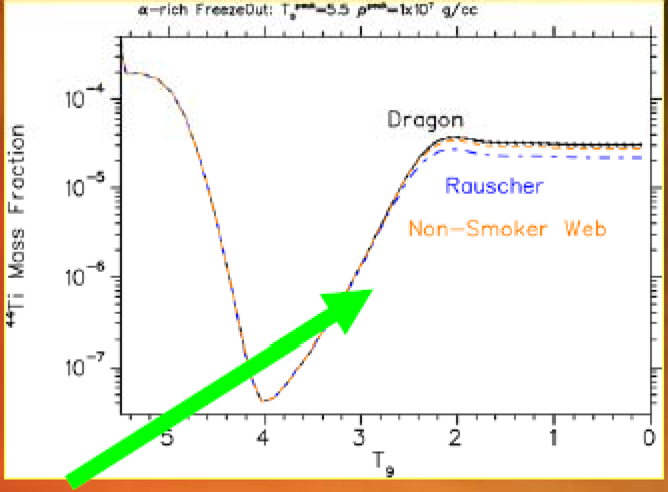
^{40}Ca(α,γ)^{44}Ti at DRAGON
^{44}Ti: youngest indicator of nucleosynthesis



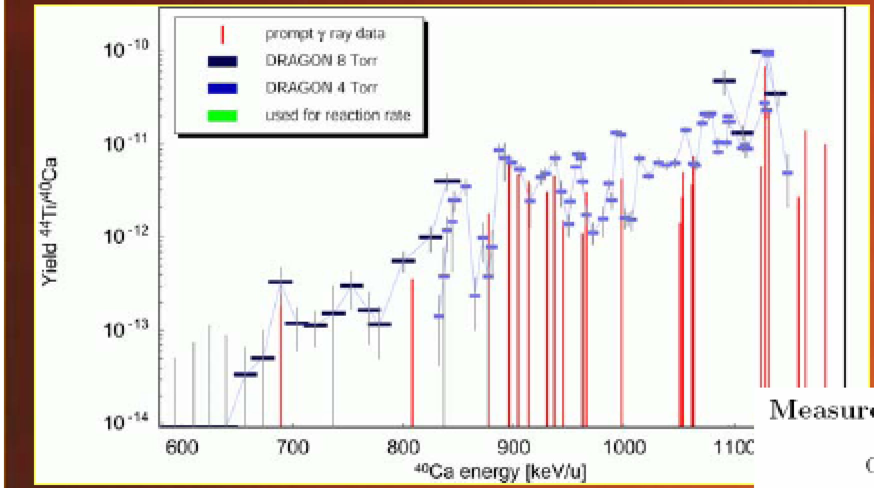
60-year half-life, observed in Cas A, SN1987A

^{44}Ti produced by ^{40}Ca(α,γ)^{44}Ti in 'alpha-rich freeze-out'

Large discrepancy between previous experiments



DRAGON measurement



40% increase of ^{44}Ti yield compared to empirical model (Rauscher *et al.* 2000)

DRAGON measured uncertainty of the reaction rate = **+/- 3%** in ^{44}Ti yield

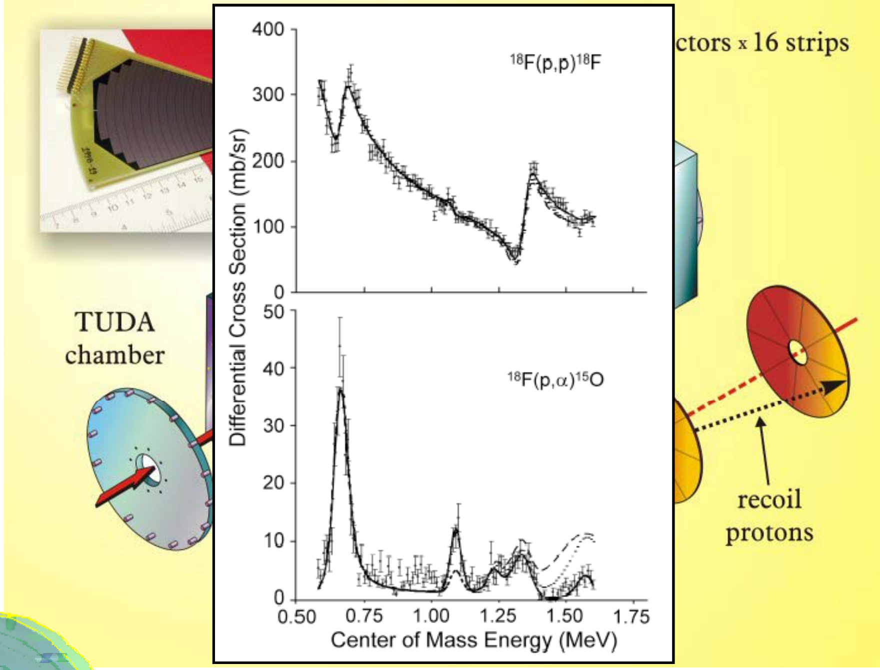
^{44}Ti yield and a ^{44}Ti/ ^{56}Ni ratio agree better with observations in Cas A and SN1987A. [cf. Nassar *et al.*, *Phys. Rev. Lett.* 96 (2006)]

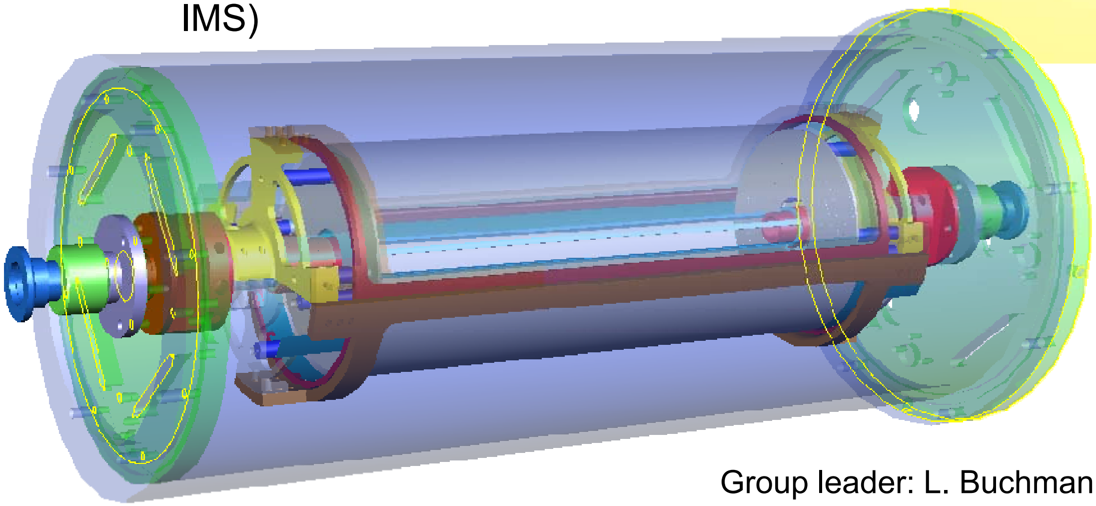
Measurement of the ^{40}Ca(α,γ)^{44}Ti reaction relevant for supernova nucleosynthesis

C. Vockenhuber,[1,*] C.O. Ouellet,[2] L.-S. The,[3] L. Buchmann,[1] J. Caggiano,[1] A.A. Chen,[2]
H. Crawford,[1] J.M. D'Auria,[4] B. Davids,[1] L. Fogarty,[1] D. Frekers,[5] A. Hussein,[6]
D.A. Hutcheon,[1] W. Kutschera,[7] A.M. Laird,[8] R. Lewis,[8] E. O'Connor,[1] D. Ottewell,[1] M. Paul,[9]
M.M. Pavan,[1] J. Pearson,[2] C. Ruiz,[1] G. Ruprecht,[1] M. Trinczek,[1] B. Wales,[2] and A. Wallner[7]

TUDA/TACTIC: charged particle reactions

- TUDA (TRIUMF-UK Detector Array): direct charged particle reactions or indirect techniques (resonant elastic scattering)
- 5 RIB experiments:
  - $^{21}Na(p,p)^{21}Na$ resonant elastic scattering
  - $^{20}Na(p,p)^{20}Na$ resonant elastic scattering
  - $^{18}F(p,\alpha)^{15}O$ direct , $^{18}F(p,p)^{18}F$ res.
  - $^{21}Na(p,\alpha)^{18}Ne$ indirect (XRB)
  - $^{7}Li(^{8}Li,^{7}Li)^{8}Li$ ANC indirect ($S_{17}(0)$ test of IMS)





TACTIC

(TRIUMF Annular Chamber for Tracking and Identification of Charged Particles

$^{8}Li(\alpha,n)^{11}B$ for BBN and r-process

$^{7}Li(^{3}He,\alpha)^{6}Li$ for BBN

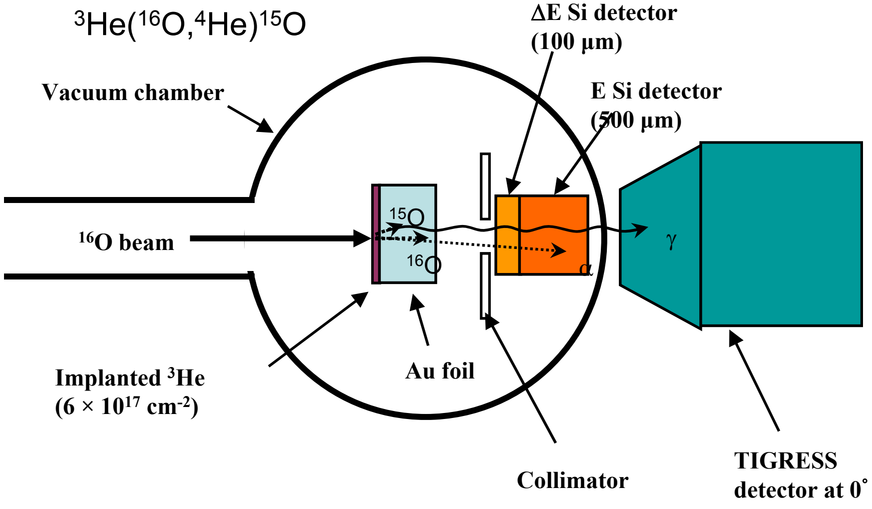
First operation 2008

Group leader: L. Buchmann

Indirect techniques: Doppler Shift Lifetime Facility

- Populate excited states of interest to measure lifetimes using Doppler Shift Attenuation Method (at ISAC I *or* ISAC II)
- Use of TIGRESS detectors
- Custom chamber and implanted targets
- $^{15}O(\alpha,\gamma)^{19}Ne$ and $^{14}N(p,\gamma)^{15}O$ studied indirectly in this way

$^{3}He(^{16}O,^{4}He)^{15}O$



ΔE Si detector (100 μm)

Vacuum chamber

E Si detector (500 μm)

^{16}O beam

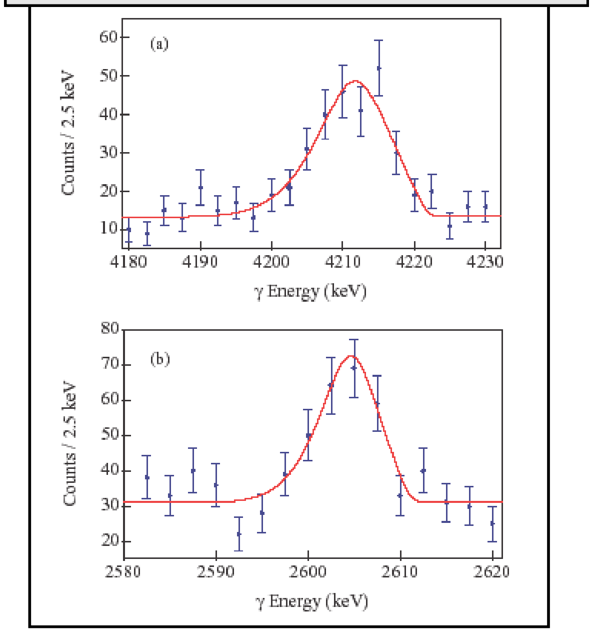
Implanted ^{3}He (6×10^{17} cm^{-2})

Au foil

Collimator

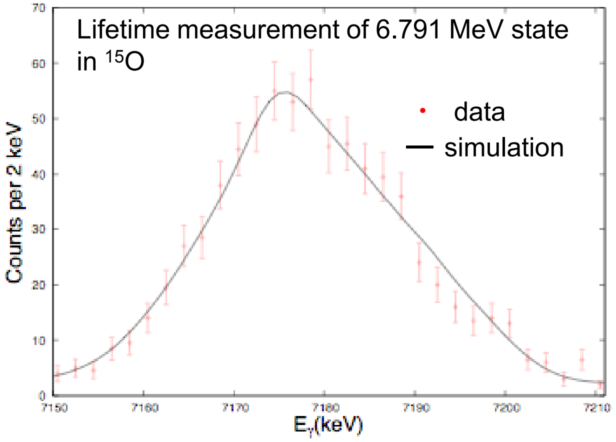
TIGRESS detector at 0˚

Measurement of Γγ for $^{19}Ne^{*}$ E_x=4.03 MeV for the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction



S. Mythili, B. Davids *et al.* Phys. Rev. C 77 (2008)

R. Kanungo *et al.* Phys. Rev. C. 74 (2007)



Lifetime measurement of 6.791 MeV state in ^{15}O

Group Leader: Barry Davids

Fundamental Physics Symmetries

TRINAT

Superallowed Beta Decay

Physics justification:

Nuclear Beta Decay

$$\frac{d^4\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto 1 + a_{\beta\nu}\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} + b_F\frac{m_e}{E_e} + \frac{\langle\vec{J}\rangle}{J}\cdot\left[A_\beta\frac{\vec{p_e}}{E_e} + B_\nu\frac{\vec{p_\nu}}{E_\nu} + D\frac{\vec{p_e}\times\vec{p_\nu}}{E_e E_\nu}\right]$$

Beta-neutrino correlation

Fierz interference (Scalar interaction)

Madame Wu's asymmetry term

Neutrino asymmetry

Angular Distribution: $W = 1 + b\, m_\beta/E_\beta + a\, v_\beta/c \cos(\theta_{\beta\nu})$

$a = 1.0$ SM; $a = -1$ for scalar boson

$$\mathcal{F}t = ft(1+\delta_{R'})(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R)} = \text{constant}$$

Q-Value, Lifetime, Branching Ratio Measurements

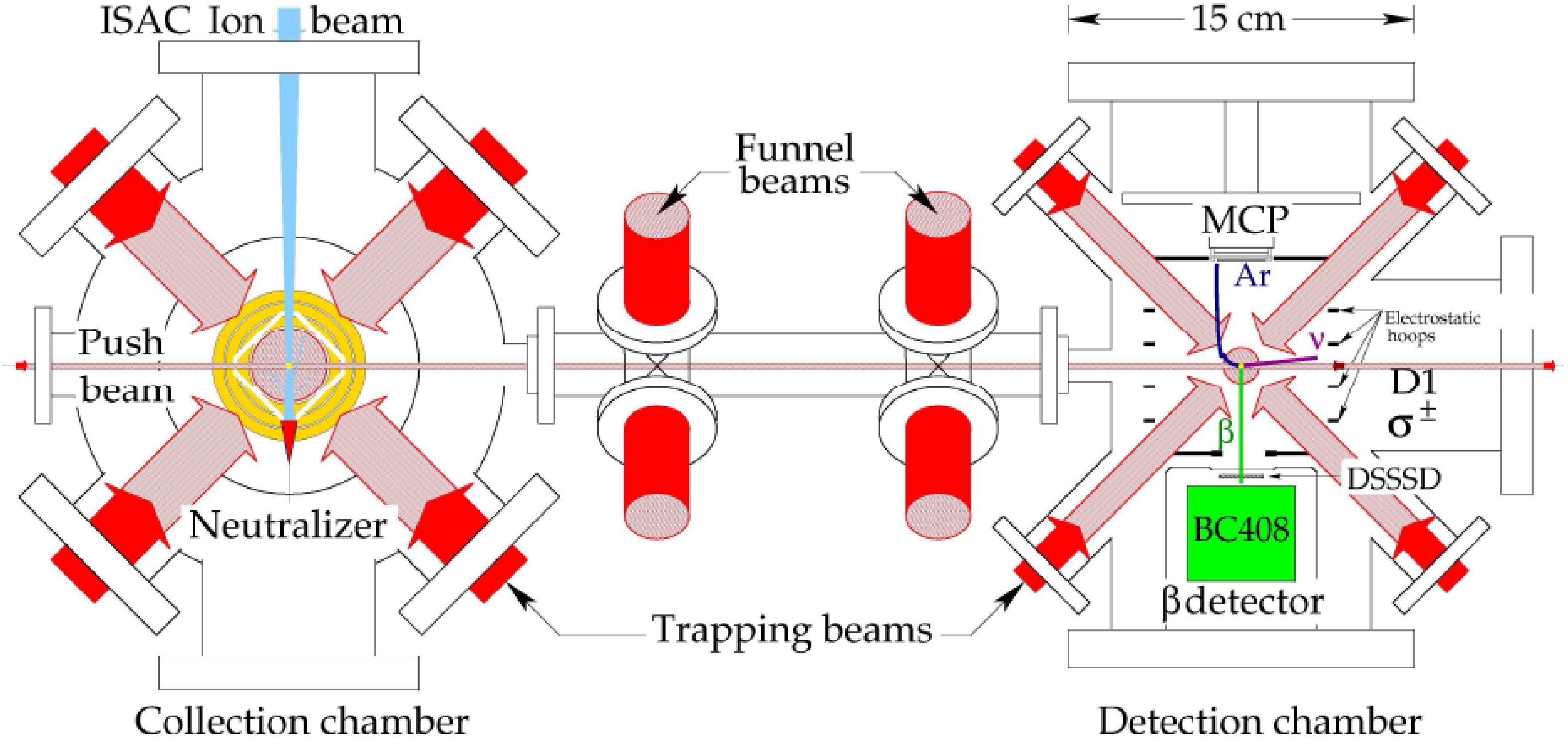
Calculated corrections (~1%) (nucleus dependent)

Inner radiative correction (~2.4%) (nucleus independent)

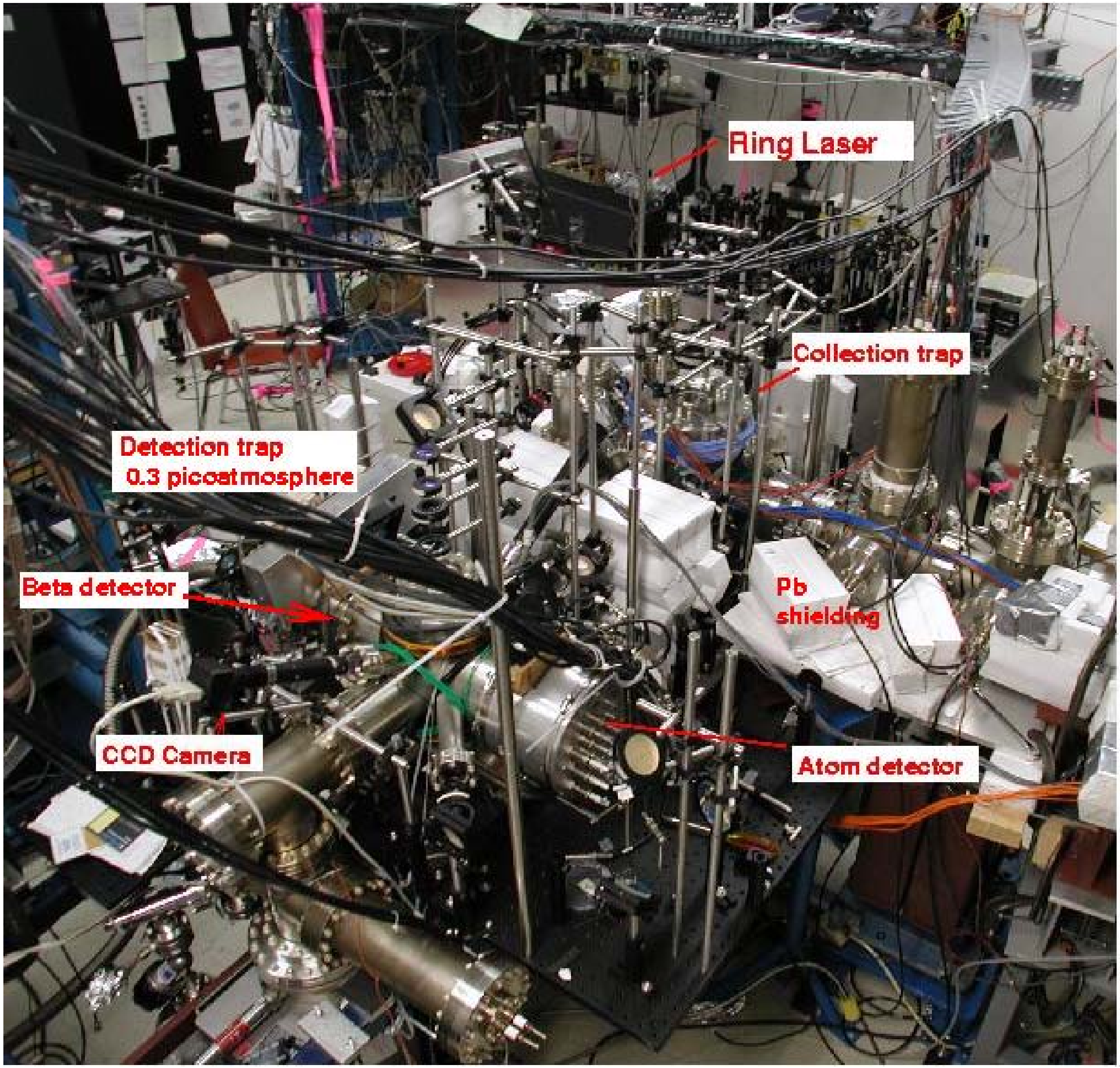
CVC Hypothesis

TRINAT
TRIUMF’s Neutral Atom Trap

- Isotope/Isomer selective
- Evade 1000x untrapped atom background by → 2nd MOT
- 75% transfer (must avoid backgrounds!); 10^{-3} capture
- 0.7 mm cloud for β-Ar^{+} $\longrightarrow$ ν momentum $\longrightarrow$ β-ν correlation
- >97% polarized, known atomically



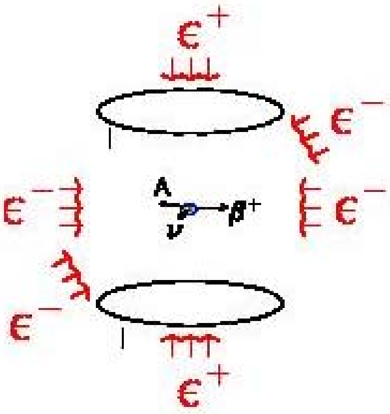
TRIUMF Neutral Atom Trap



The pressure of laser light traps atoms of unstable isotopes in a 1mm–sized cloud.

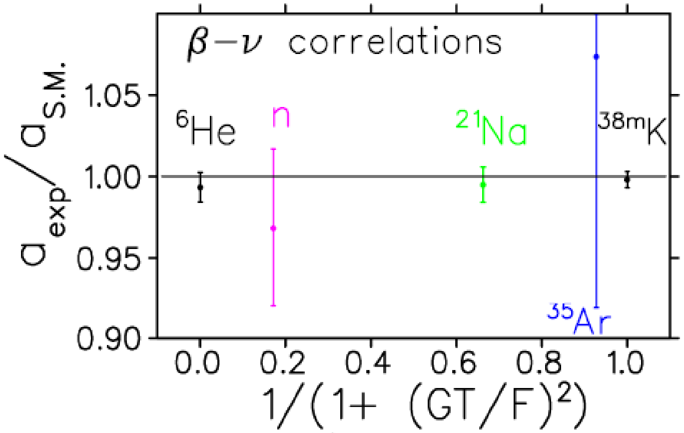
The final atoms after decay have small kinetic energies (~100 eV) but freely escape the trap so we can measure their momentum. In 'beta decay' we measure the electron and atom momentum and deduce the (otherwise invisible) neutrino momentum.

← ISAC ion beam

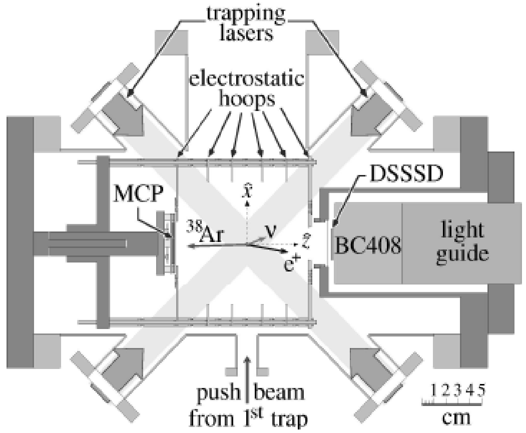


TRINAT Results and Impact

TRIUMF Neutral atom trap: β decay correlations



- **Upgrades in progress, goals 5-10 X better:**
  - **^{38m}K β-ν correlation: Gorelov PRL 2005, best general limits on scalars coupling to 1st generation**
  - **$^{37}\vec{K}$: ν spin asymmetry Melconian PLB 2007 $B_\nu/B_\nu^{SM} = 0.982 \pm 0.026 \pm 0.017$**

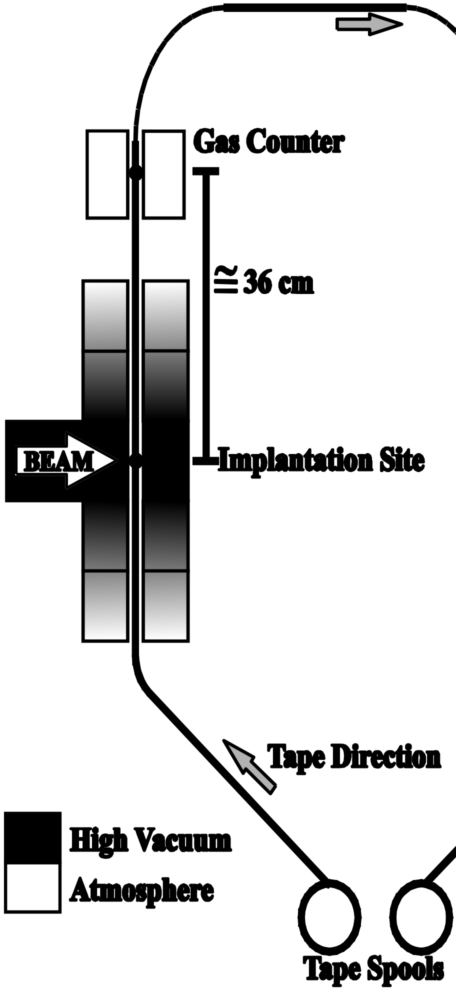


- **Singles recoil spin asymmetry ^{80}Rb Pitcairn PRC 2009 $A_{recoil}=0.015\pm0.029\pm0.019$ Complementary constraints on tensor interactions**

goals: scalar, tensor interactions from SUSY produce $\sim$ 0.001 effects (Profumo, Ramsey-Musolf, Tulin PRD 2007)

Searching for exotic massive particles in 2-body decay

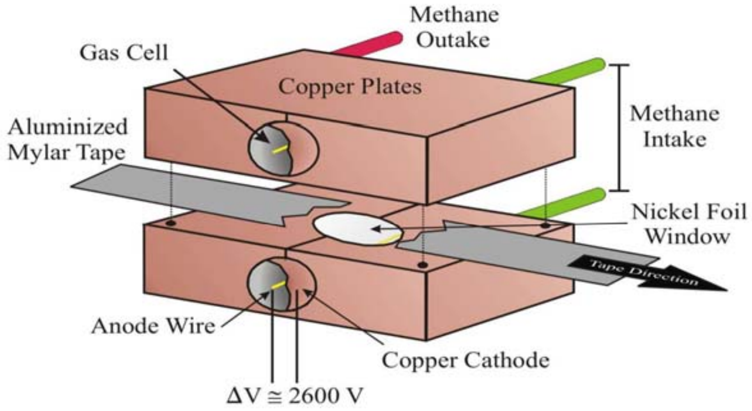
Precision Lifetime Measurements at ISAC
Beta-decay tape station



4 π gas-proportional β counter setup

Isotopes Measured
(<0.05% Precision)

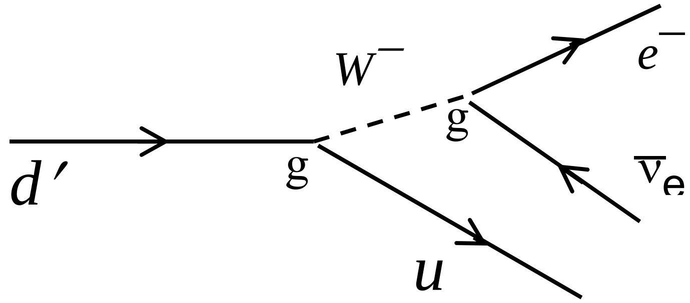
^{74}Rb, 64.761 ± 0.031 ms
^{62}Ga, 116.100 ± 0.025 ms
^{18}Ne, 1.667 ± 0.008 s
^{26}Na, 1.0717± 0.0028 s



G. Ball

The Cabibbo-Kobayashi-Maskawa (CKM) matrix

- The CKM matrix plays a central role in the Standard Model
  describes the mixing of different quark generations:
  → weak interaction eigenstates ≠ quark mass eigenstates



ν_e	ν_μ	ν_τ
e^-	μ^-	τ^-

u	c	t
d	s	b

$$|d'\rangle = V_{ud}|d\rangle + V_{us}|s\rangle + V_{ub}|b\rangle$$

- In the Standard Model the CKM describes
- a unitary transformation.

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} \boxed{V_{ud}} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The first row of the CKM matrix provides the most demanding experimental test of this unitarity condition.

V_{ud} : The Responsibility of Low-Energy Nuclear Physics

To first order, β decay ft values can be expressed as:

phase space (Q-value)

constants

$$f\,t = \frac{K}{|M_{fi}|^2\, g^2}$$

half-life, branching ratio

Weak coupling strength

matrix element

For the special case of $0^+ \rightarrow 0^+$ (pure Fermi) β decays between isobaric analogue states (superallowed) the matrix element is that of an isospin ladder operator:

$$|M_{fi}|^2 = (T - T_Z)(T + T_Z + 1) = 2 \quad (\text{for } T=1)$$

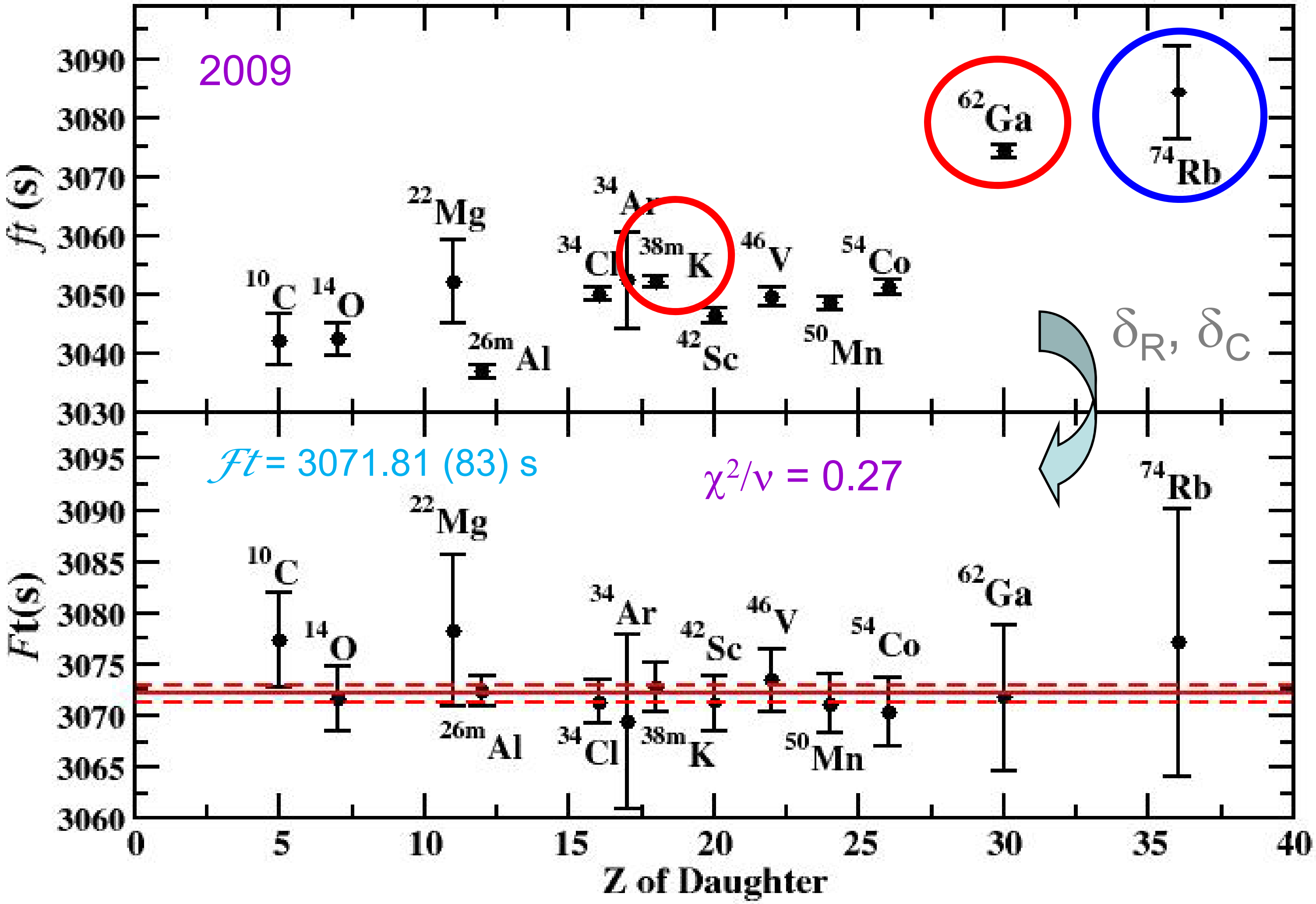
Strategy: Measure superallowed ft-values, deduce G_V and V_{ud}:

Vector coupling constant → $G_V^2 = \dfrac{K}{2\,ft}$

$|V_{ud}| = G_V / G_F$ ← Fermi coupling constant

Superallowed Fermi β Decays

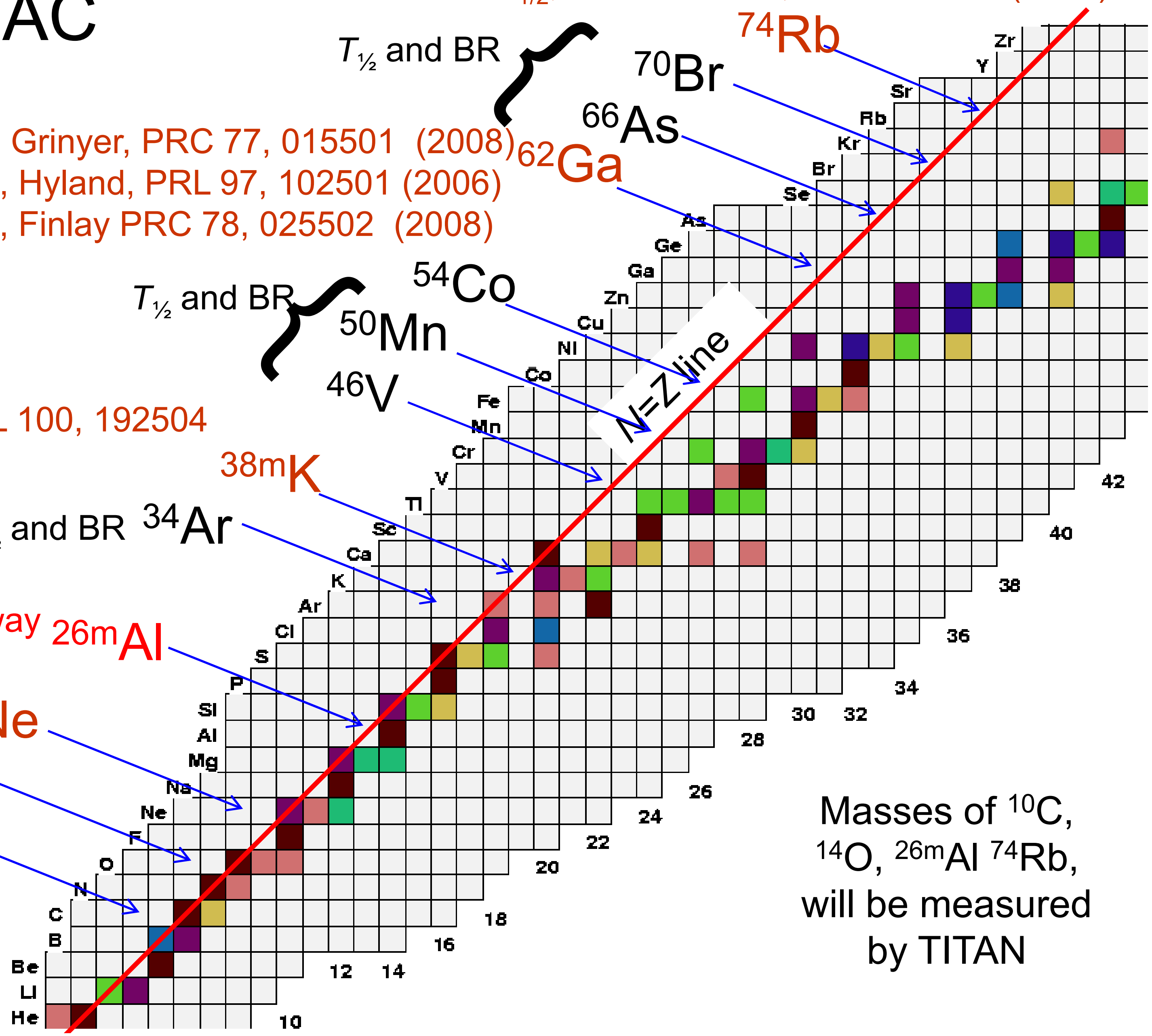
^{38m}K: BR ^{62}Ga: $T_{1/2}$, BR ^{74}Rb: $T_{1/2}$, BR



$V_{ud} = 0.97425(22)$ $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99995(61)$

JCH & IT, PRC 79(2009)

Future Superallowed Studies at ISAC



$T_{1/2}$, G.C. Ball *et al*, PRL 86 1454 (2001)

^{74}Rb

$T_{\frac{1}{2}}$ and BR

^{70}Br

^{66}As

$T_{\frac{1}{2}}$, Grinyer, PRC 77, 015501 (2008)
BR, Hyland, PRL 97, 102501 (2006)
BR, Finlay PRC 78, 025502 (2008)

^{62}Ga

$T_{\frac{1}{2}}$ and BR

^{54}Co

^{50}Mn

^{46}V

BR, *Leach et al.*, PRL 100, 192504 (2008)

^{38m}K

$T_{\frac{1}{2}}$ and BR ^{34}Ar

$T_{\frac{1}{2}}$ and BR, P. Finlay
Analysis currently underway

^{26m}Al

$T_{\frac{1}{2}}$, Grinyer et al, PRC 76 25503 (2007)

^{18}Ne

$T_{\frac{1}{2}}$ by β and γ counting

^{14}O

^{10}C

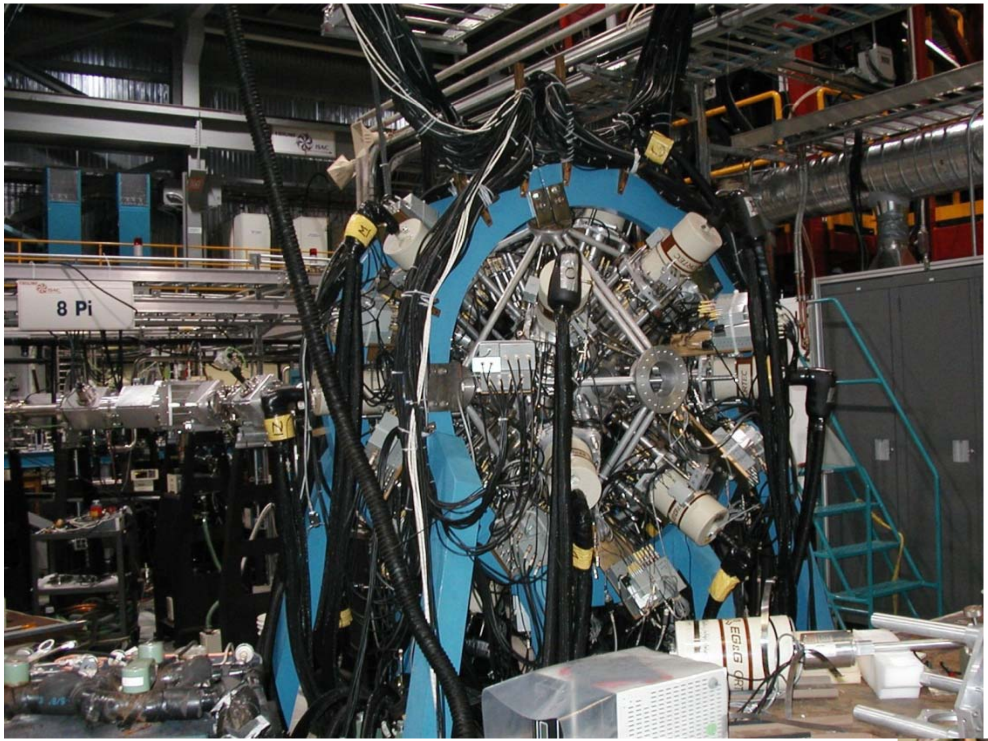
Masses of ^{10}C, ^{14}O, ^{26m}Al ^{74}Rb, will be measured by TITAN

G. Ball

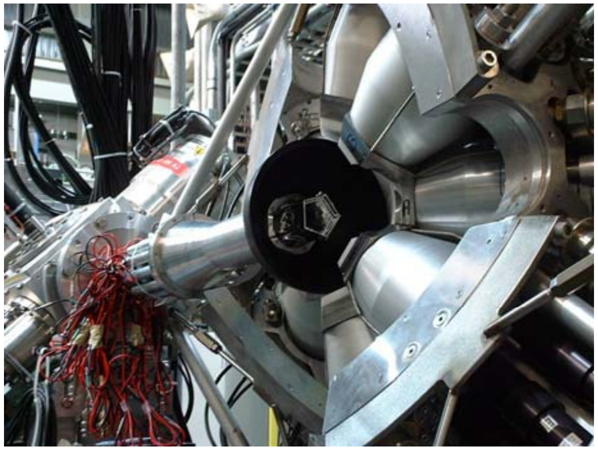
Nuclear Structure

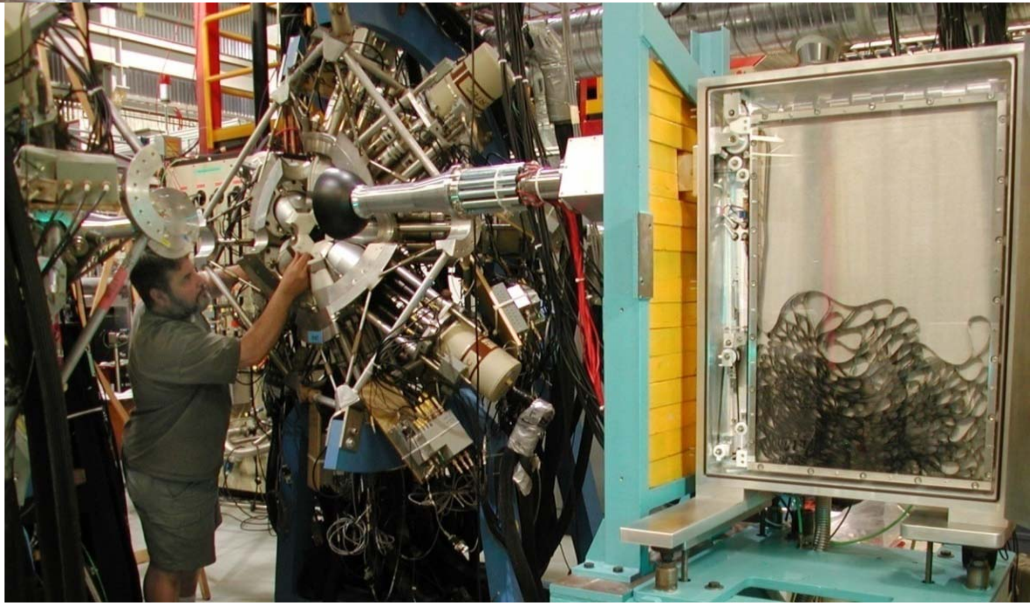
- Halo Nuclei Studies

The 8π at TRIUMF

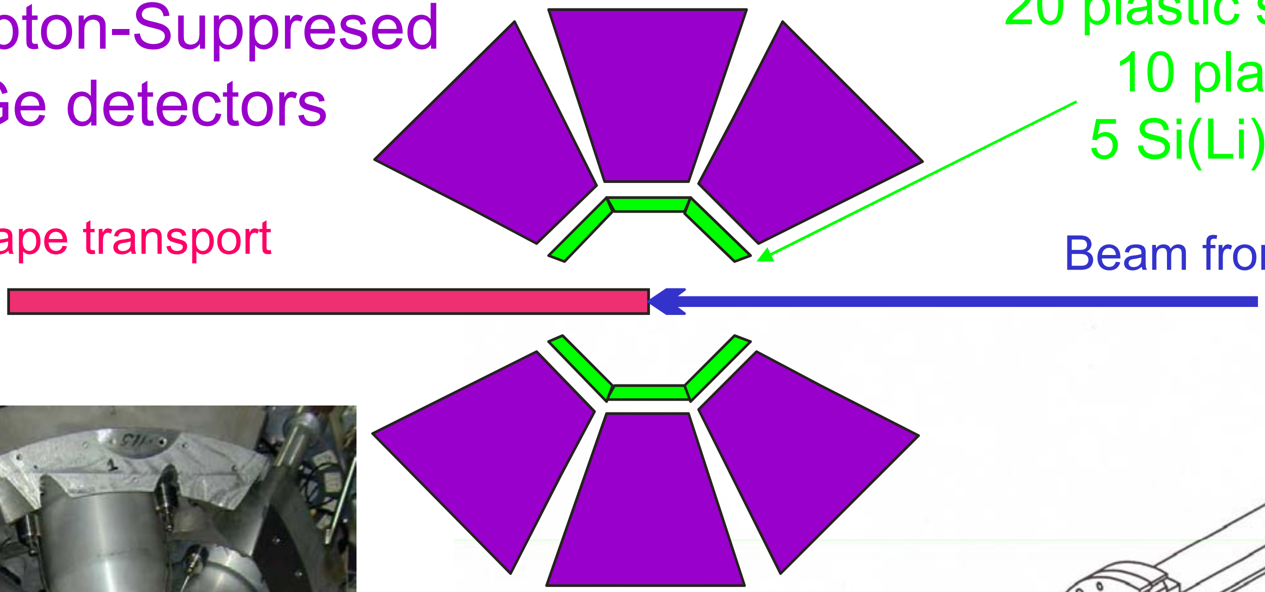


- 20 25% HPGe w/ Suppressors
- Endless loop moving tape system (LSU)
- Programmable states (beam on/off, tape move, trigger veto)
- Inner plastic scintillator array,
- Options: Si(Li), BaF_2
- For ^{19}Ne:
  - Plastics for lifetime
  - HPGe for branching ratio





8π Spectrometer and SCEPTAR at ISAC-I



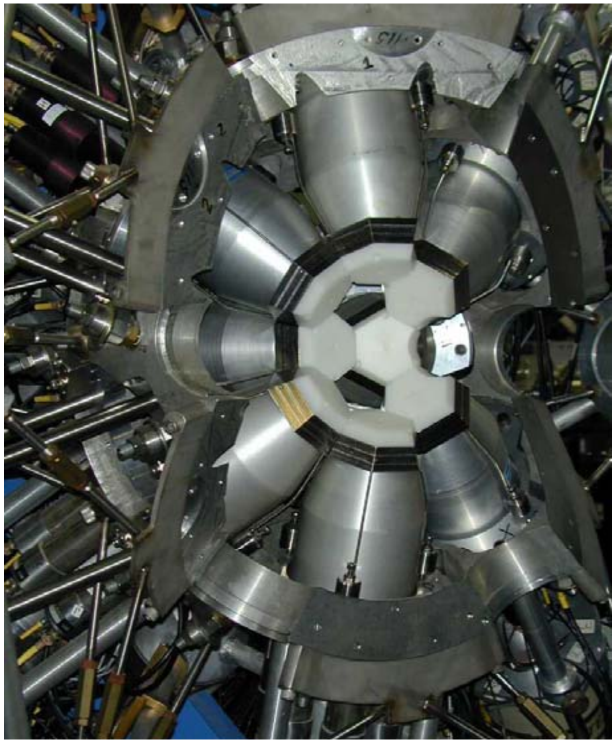
20 Compton-Suppresed HPGe detectors

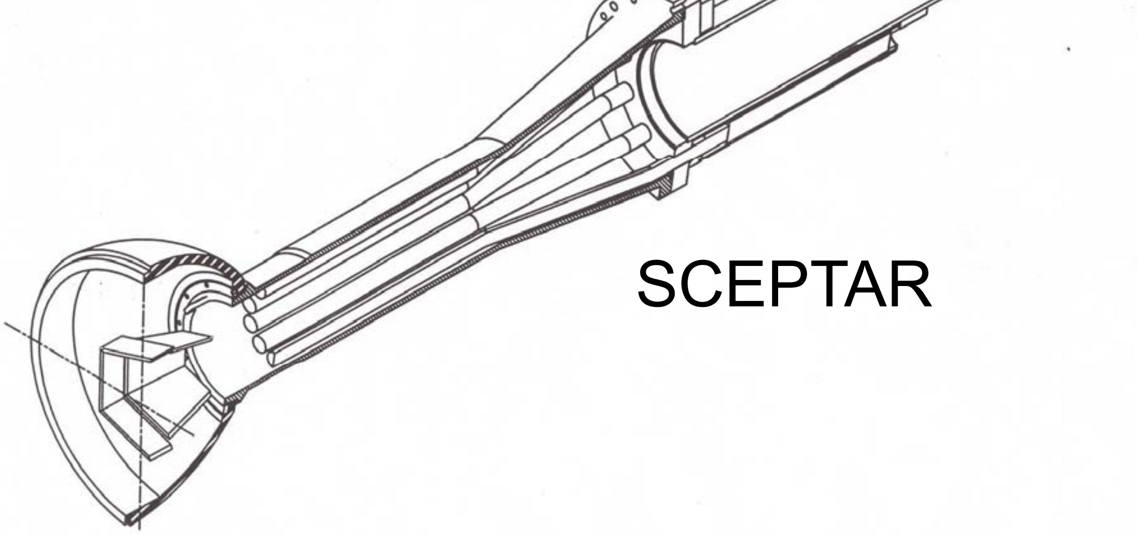
20 plastic scintillators or
10 plastics and
5 Si(Li) detectors

tape transport

Beam from ISAC

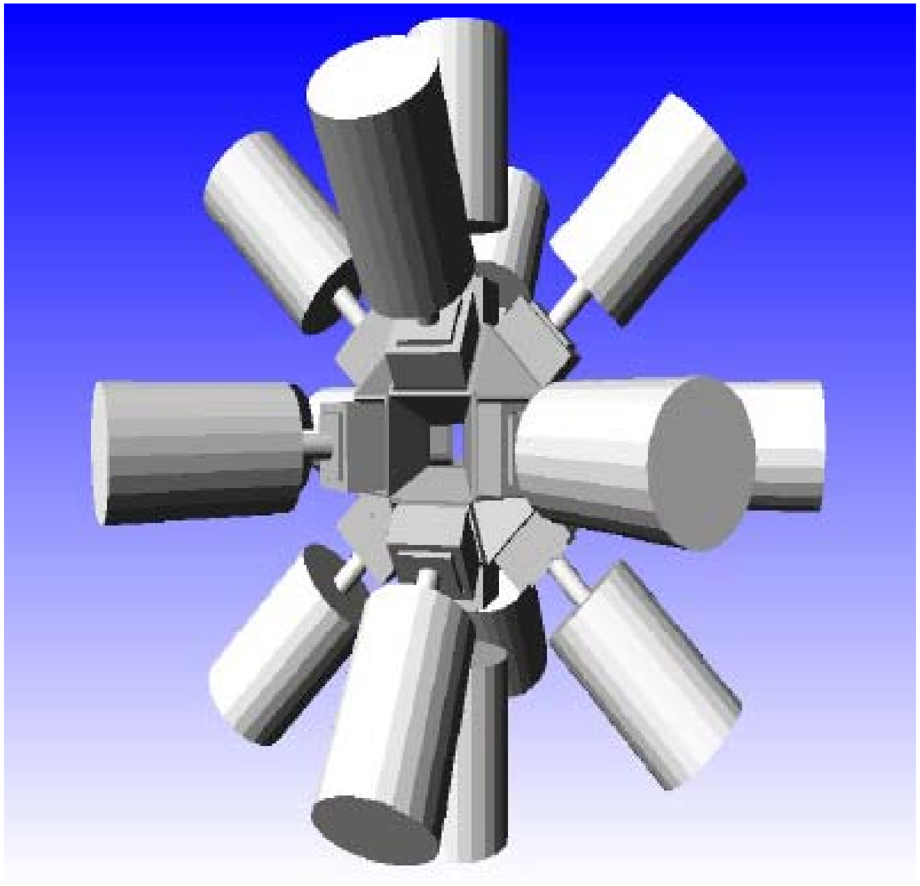
8π

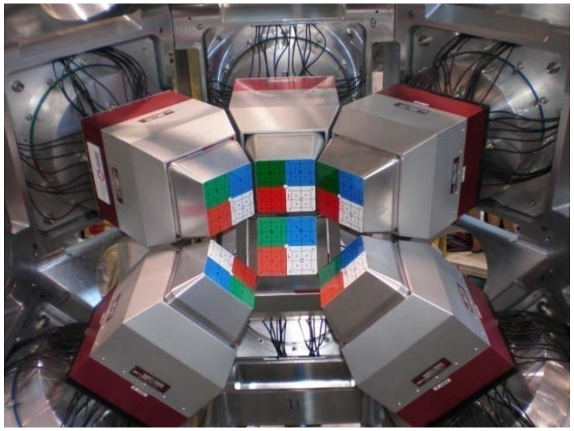


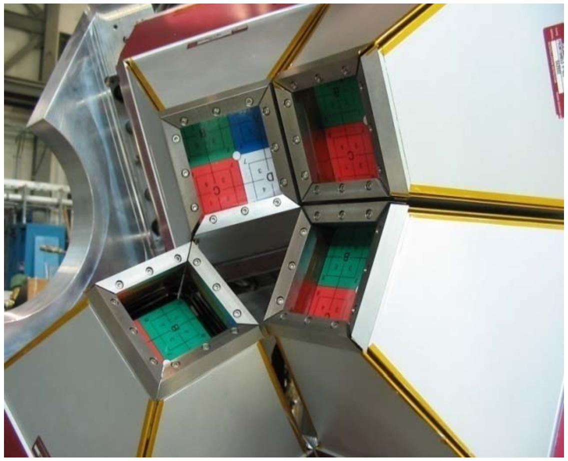


SCEPTAR

TRIUMF-ISAC Gamma-Ray Escape-Suppressed Spectrometer (TIGRESS):





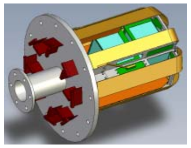


Four ~40% n-type HPGe crystals close-packed in a four-leaf clover geometry.

32-fold segmentation of the outer contacts provide position resolution.

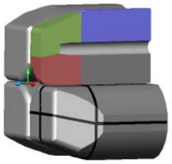
Even more powerful when combined with auxiliary detectors.

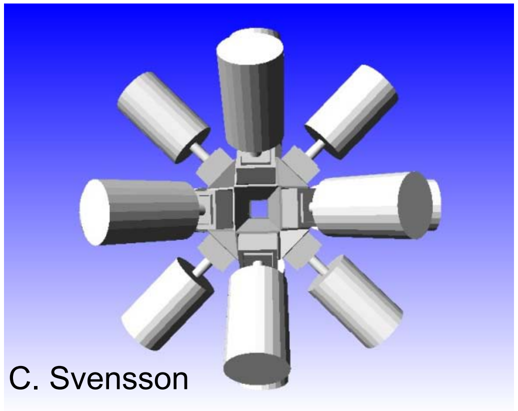
University of Guelph, McMaster University, Université de Montréal, University of Toronto,
Université Laval, Simon Fraser University, and TRIUMF



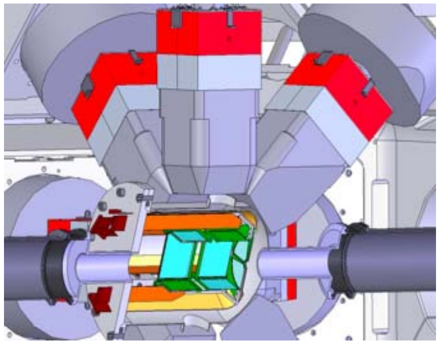
TIGRESS Ge Gamma Array

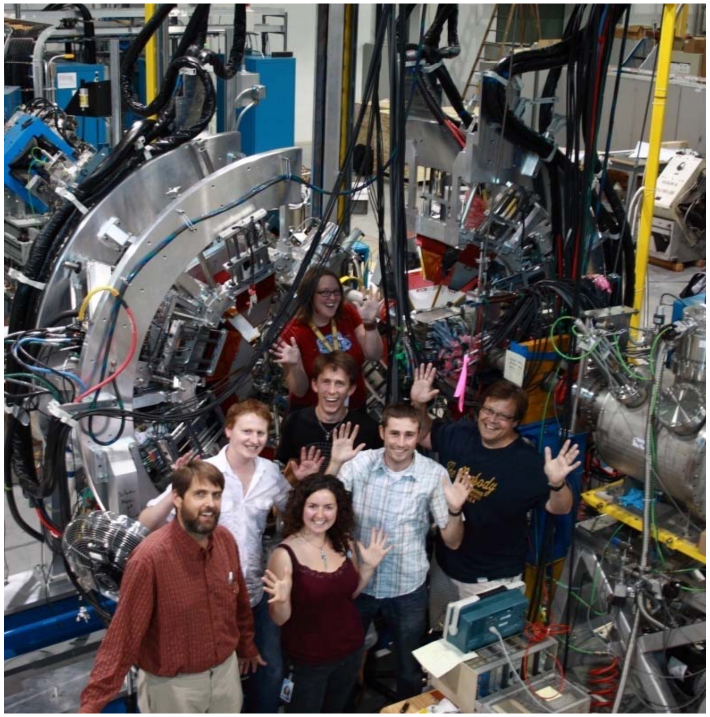
and SHARC Silicon barrel

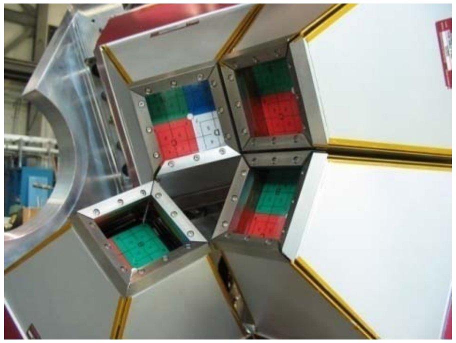


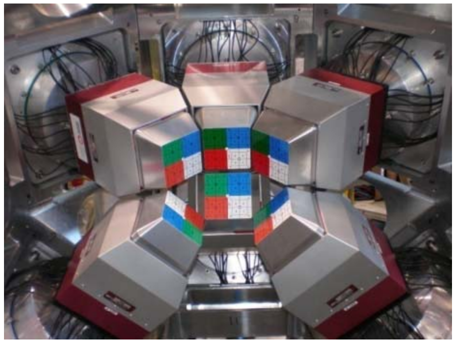


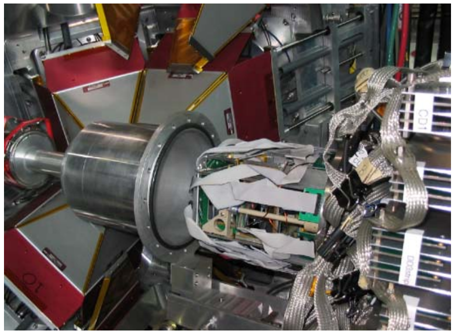
C. Svensson

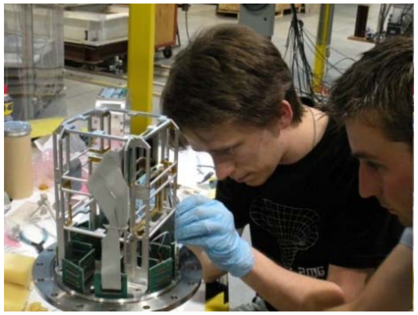


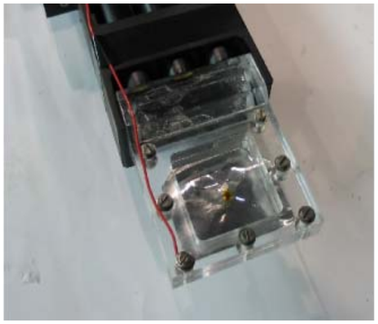


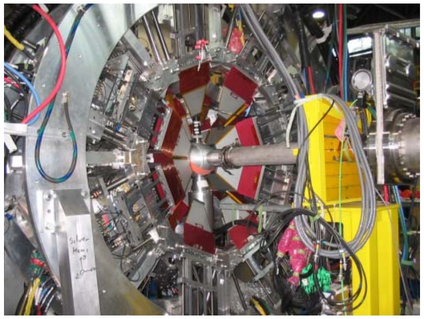












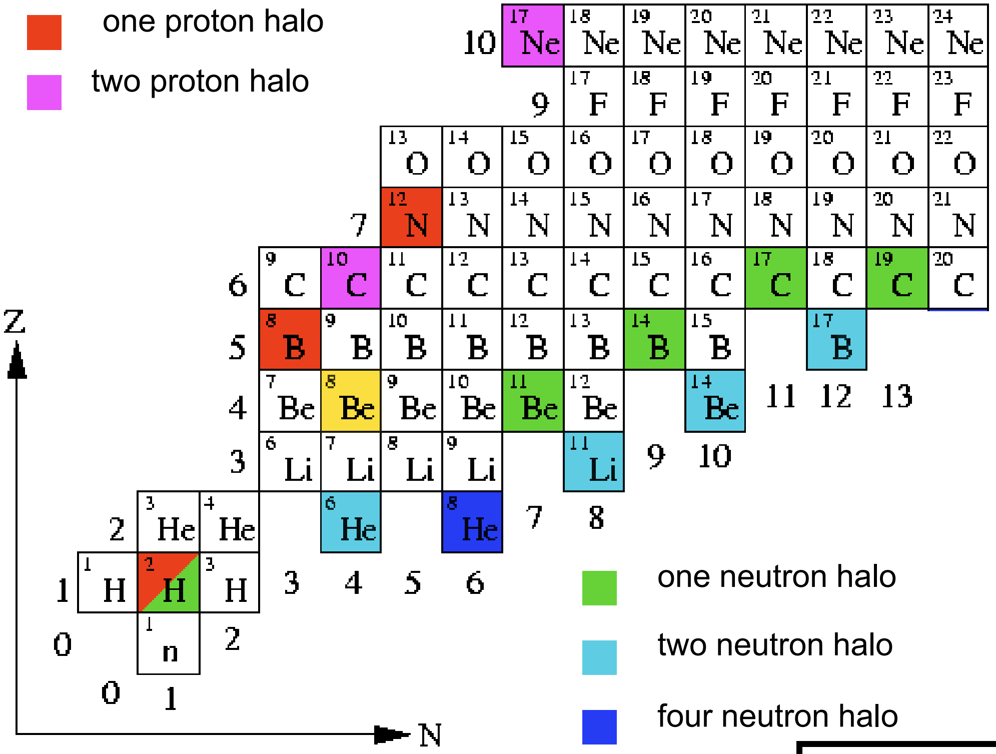
Halo Nuclei

(radius>> $r_o A^{1/3}$)

Nuclear halos

🟥 one proton halo

🟪 two proton halo



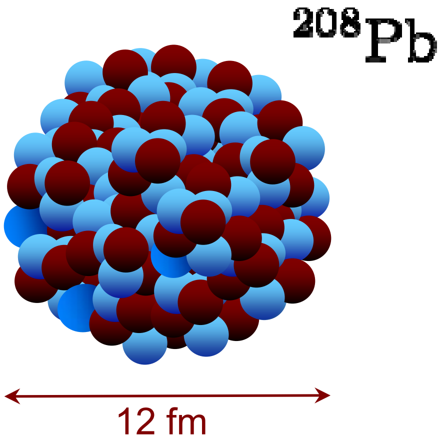
🟩 one neutron halo

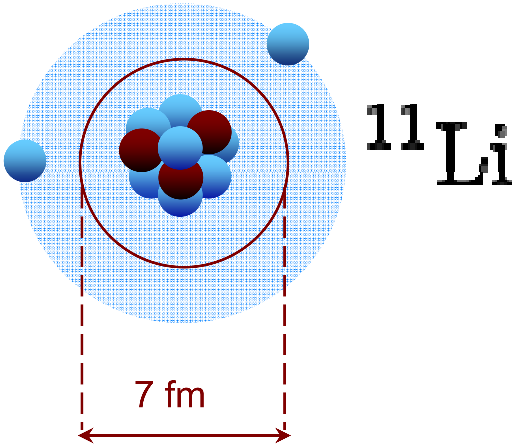
🟦 two neutron halo

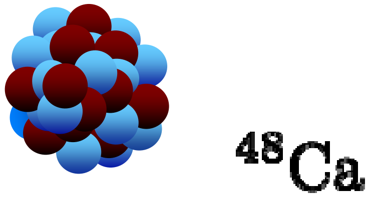
🟦 four neutron halo

- Short-lived, hard experiments
- few nucleon system
  - challenge for theory at extreme conditions
  - address with series of experimental approaches and systems @ ISAC

Halo	$T_{1/2}$
^{8}He	119 ms
^{11}Li	8.8 ms
^{14}Be	4.4 ms







Selected Recent Publications on Halo Nuclei Experiments at TRIUMF-ISAC

- ☐ ^{11}Li β-n-DSAM : F. Sarazin *et al.*, Phys. Rev. C 70, 031302R (2004), and C. Mattoon et al., PRC 80, 034318 (2009) [*CSM*]
- ☐ ^{11}Li β-n: Y. Hirayama *et al.*, Phys. Lett. B611, 239 (2005) [*Osaka*]
- ☐ ^{11}Li charge radius: R. Sanchez *et al.*, PRL 96, 033002 (2006) [*GSI, U. Tübignen*]
- ☐ ^{11}Li β-charged particle: R. Raabe *et al.*, PRL 101, 212501 (2008) [*K.U.Leuven*]
- ☐ ^{11}Li two-neutron transfer (p,t): Tanihata, Savajols *et a*l, PRL 100, 192502 (2008) [*GANIL,Osaka*]
- ☐ ^{9,11}Li mass: M. Smith *et al.*, PRL 101, 202501 (2008)
- ☐ ^{8}He mass: V. Rykov *et al.*, PRL 101, 202301 (2008)
- ☐ ^{11}Be mass: R. Ringle *et al.*, PLB 675, 170 (2009)

The Maya Experiments

1. The p(^{11}Li,^{9}Li)t reaction at 3 MeV/u
   - First study at ISAC 2
   - Large international group
   - time projection chamber from GANIL
   - Studying correlations between halo n
   - 2500-5000 pps of ^{11}Li on target
   - transitions to gs and 1st ex state

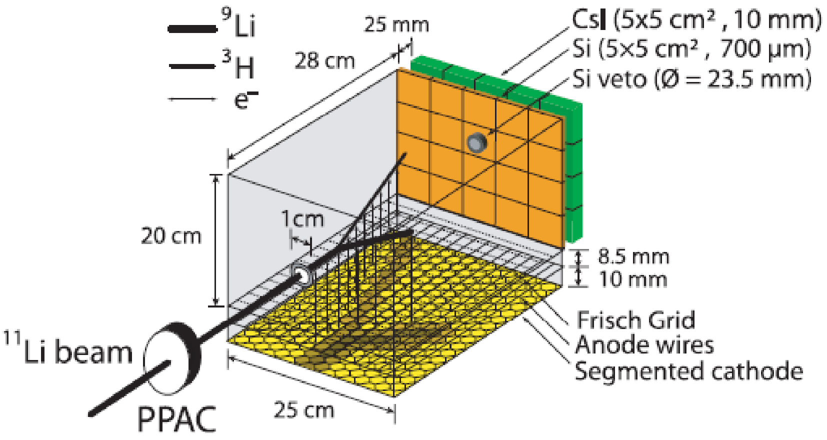
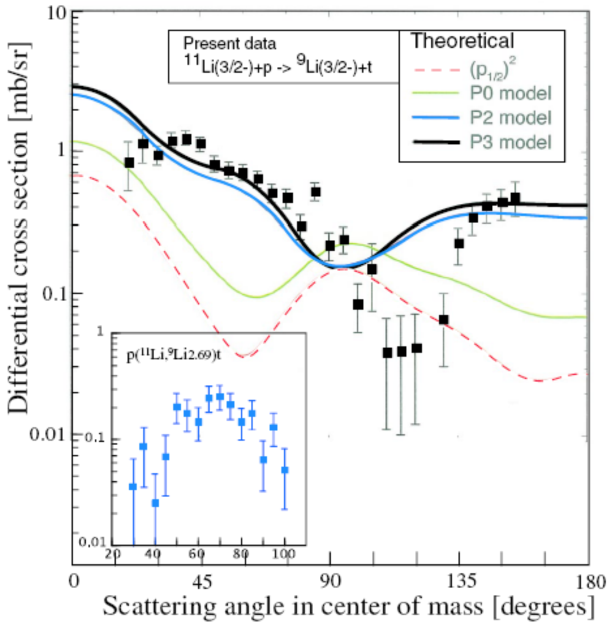


FIG. 1. (Color online) A schematic drawing of the MAYA detector. The ^{11}Li beam is incident from the left, and ionization electrons drift down to the anode wires. Projections of the charged particles trajectories are recorded on the honeycomb segmented cathode. Escaping particles hit the backside Si + CsI wall.



2. Mass of Li from the p,t reaction
   - mass derived from the Q value of the p,t reaction
   - Q value of 8.119(22) MeV
   - S_{2n} = 363(22) MeV consistent with results from TITAN and MISTRAL

Nuclear Masses

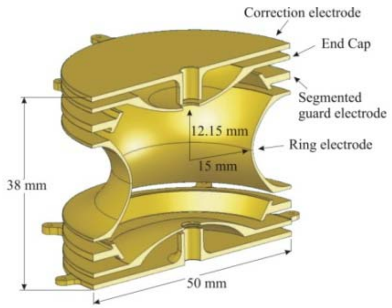
TITAN mass measurement system

Jens Dilling

- **Penning trap mass measurements on isotopes with short half-life $T_{1/2} \approx 10$ ms and low production yields (≈ 10 ions/s)**
- **Only online spectrometer to use highly charged ions**

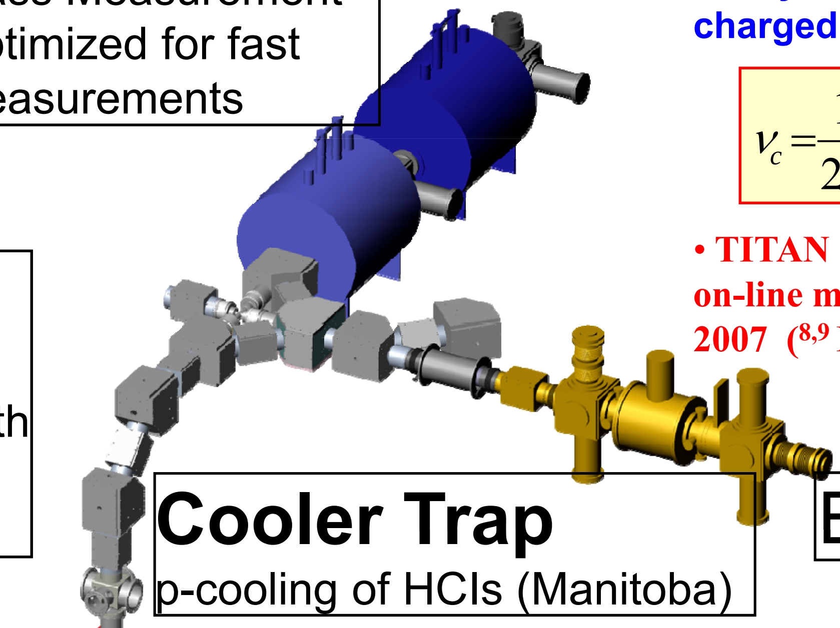
$$\nu_c = \frac{1}{2\pi}\cdot\frac{q}{m}\cdot B \qquad \frac{\delta m}{m} \approx \frac{m}{T_{RF}\cdot q\cdot B\cdot\sqrt{N}}$$

- **TITAN started April 2003 (NSERC), first on-line mass measurements carried out Sept. 2007 (^{8,9}Li, then ^{8}He, then ^{11}Li (and more)**



Penning Trap

Mass Measurement
Optimized for fast measurements



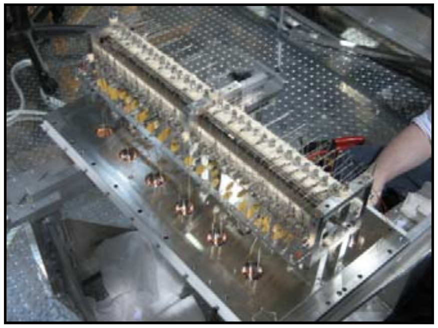
RFQ

Cooling and Bunching
Sq-W driven system with
He or H coolant
reverse extraction

Cooler Trap

p-cooling of HCIs (Manitoba)

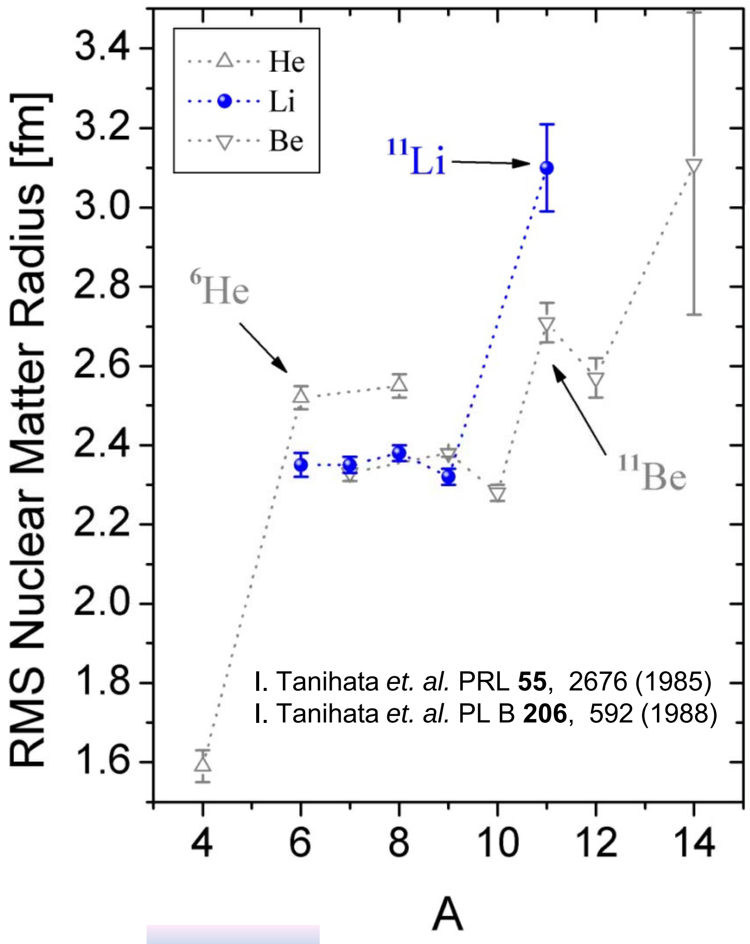
EBIT charge state breeding



ISAC Beam

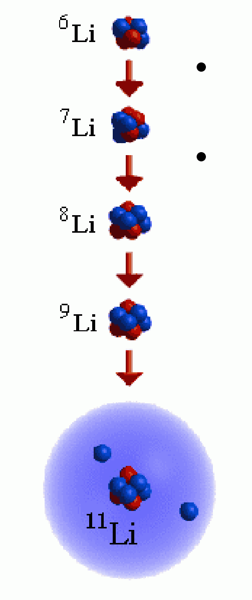
**TRIUMF, McGill University,
University of Muenster,
MPI-K Heidelberg, GANIL,
TU Munich, University of Windsor,
Colorado SoM, Universite Paris-Sud,
University of Manitoba, Yale,
University of British Columbia,
Simon Fraser University**

Strange form of matter: Halo nuclei
an ‘old’ phenomena, but new methods at ISAC



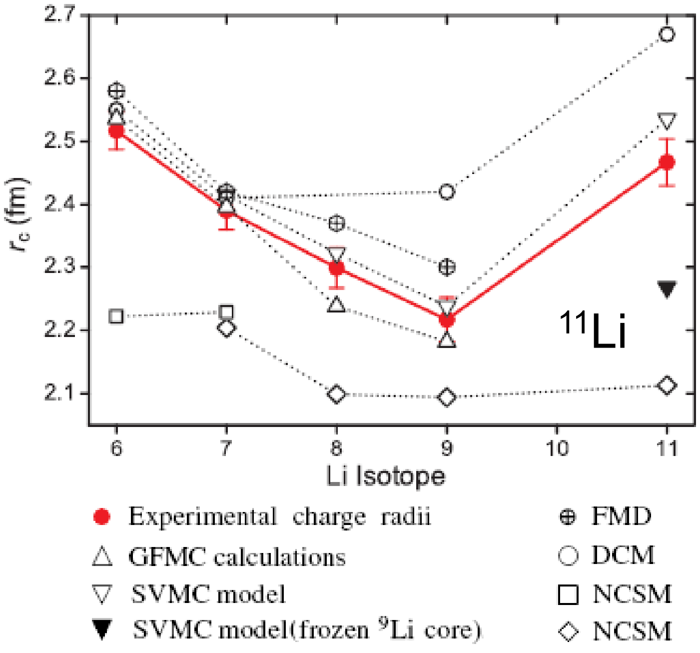
I. Tanihata *et. al.* PRL **55**, 2676 (1985)
I. Tanihata *et. al.* PL B **206**, 592 (1988)

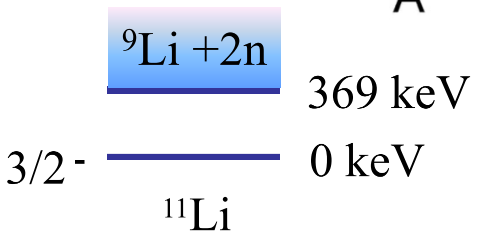
^{6}Li	^{7}Li	^{8}Li	^{9}Li	^{11}Li
∞	∞	838 ms	178 ms	8.6 ms
1	3/2	2	3/2	3/2



- In 1985 Tanihata et al. fired light nuclei at Beryllium, Carbon and Aluminum targets
- They found the radius (mass distribution) of ^{11}Li to be much larger than expected
- Extra neutrons or protons on forbidden orbits

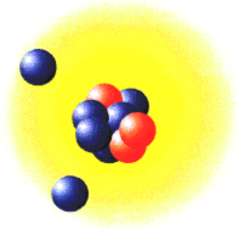
Charge Distribution@ISAC
R. Sánchez *et al.*, PRL 96, 033002 (2006)
Nature Physics 2, 145 (2006)



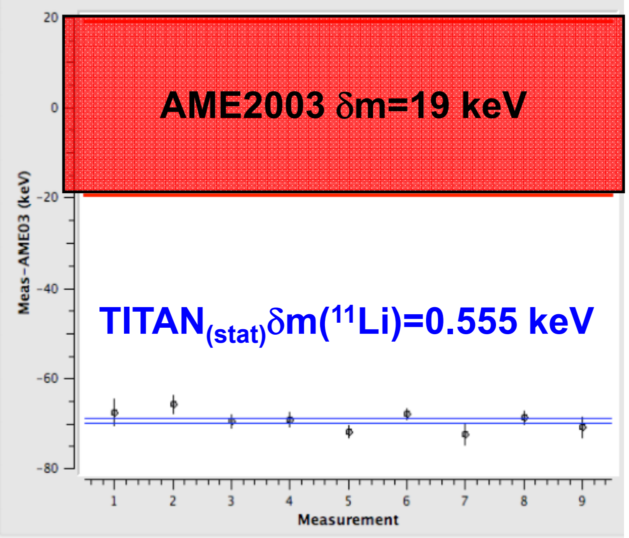


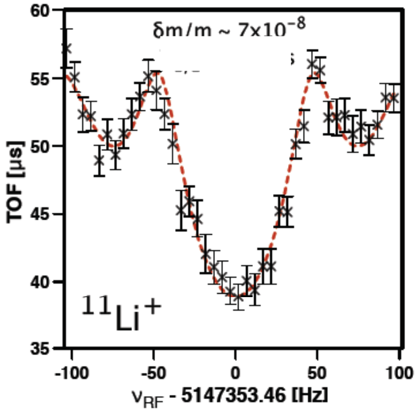
Very low binding of neutrons

Halo mass measurements: ^{11}Li

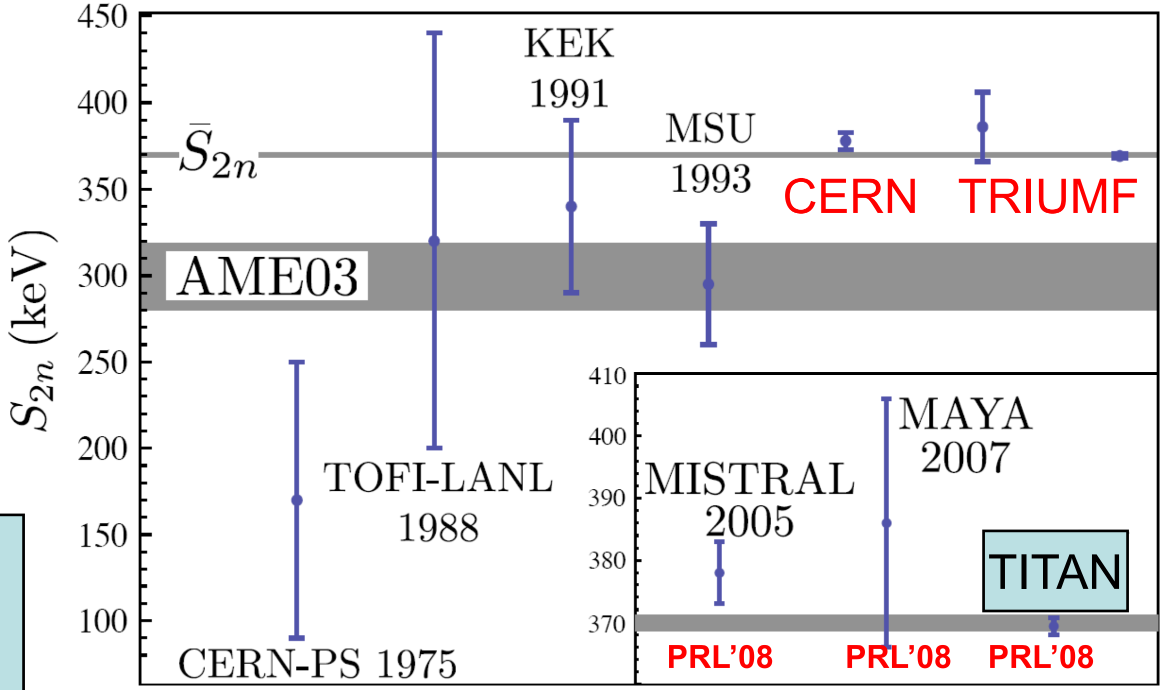


- **TITAN mass measurement of ^{6,7,8,9,11}Li**
- **Improved precision, S_{2n} improved by factor 7**
- **Shortest-lived isotope ($T_{1/2}$=8.8ms) for Penning trap mass measurement!**
- **Final analysis δm = 650 eV**
- **M. Smith et al PRL 101, 202501 (2008)**
- **Re-evaluation of radius, and comparison to theory**



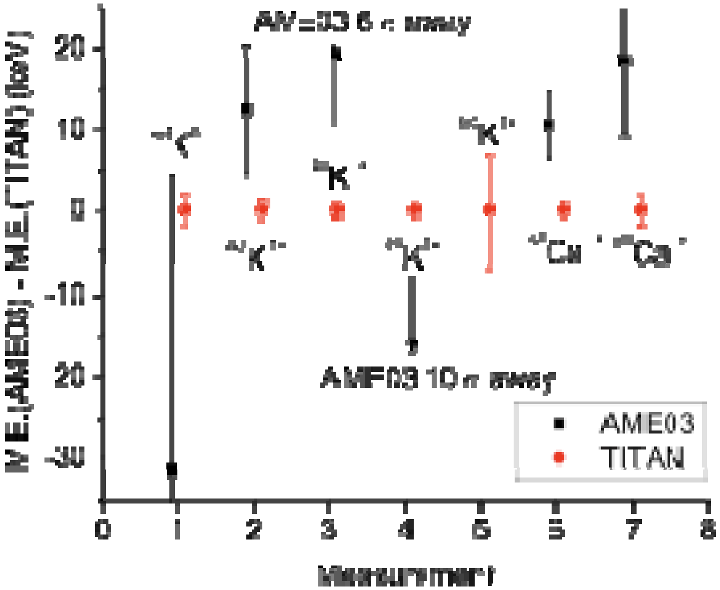


Fast measurement due to unique & rapid ion preparation with TITAN.

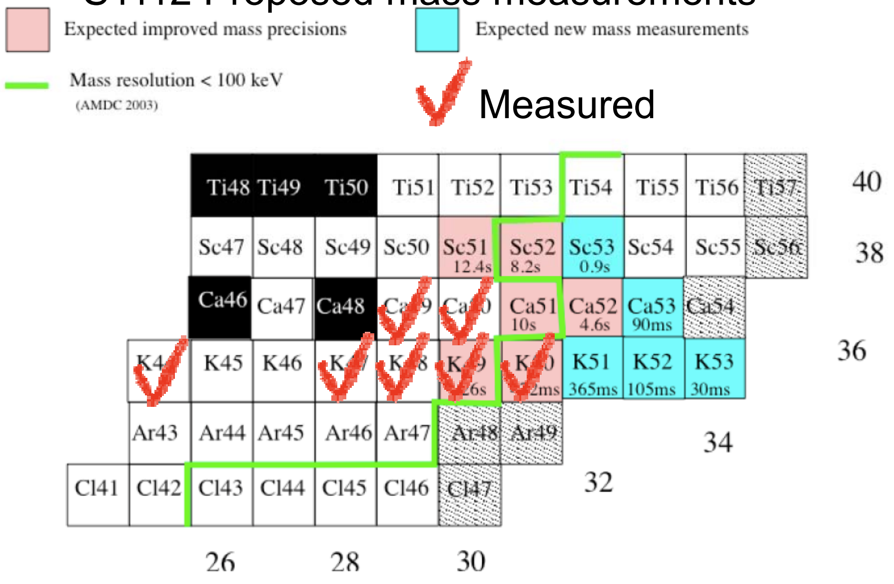


TITAN Masses – K Isotopes

- $^{44}K^{4+}$: First on-line mass measurement using charged bred ions from the EBIT
- $^{47-50}K^{1+}$ and $^{49,50}Ca^{1+}$: masses improved by factor of up to 100
- $^{48}K^{1+}$ and $^{49}K^{1+}$: deviations of 6 and 10 σ from AME03



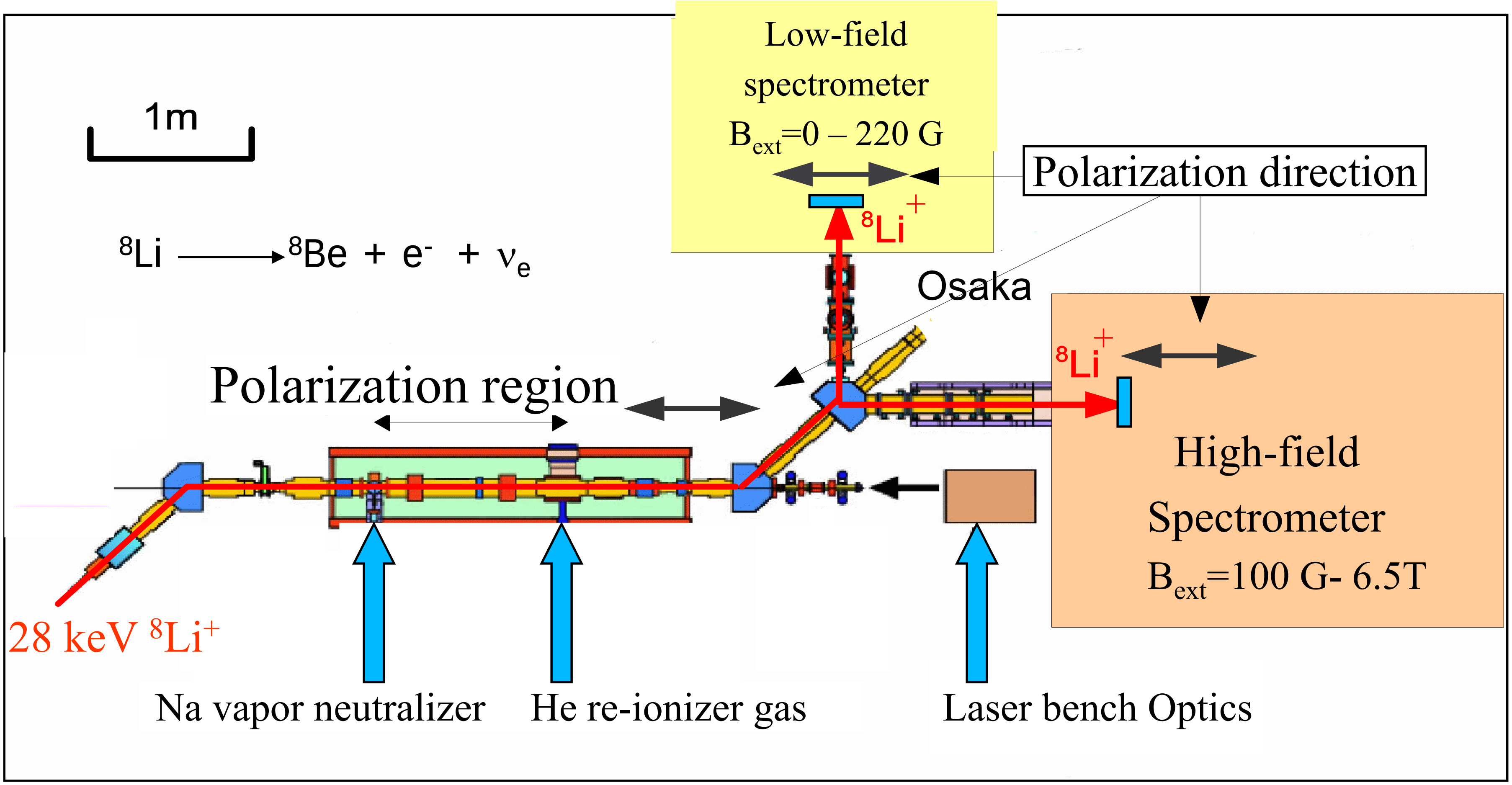
S1112 Proposed mass measurements



Condensed Matter Physics

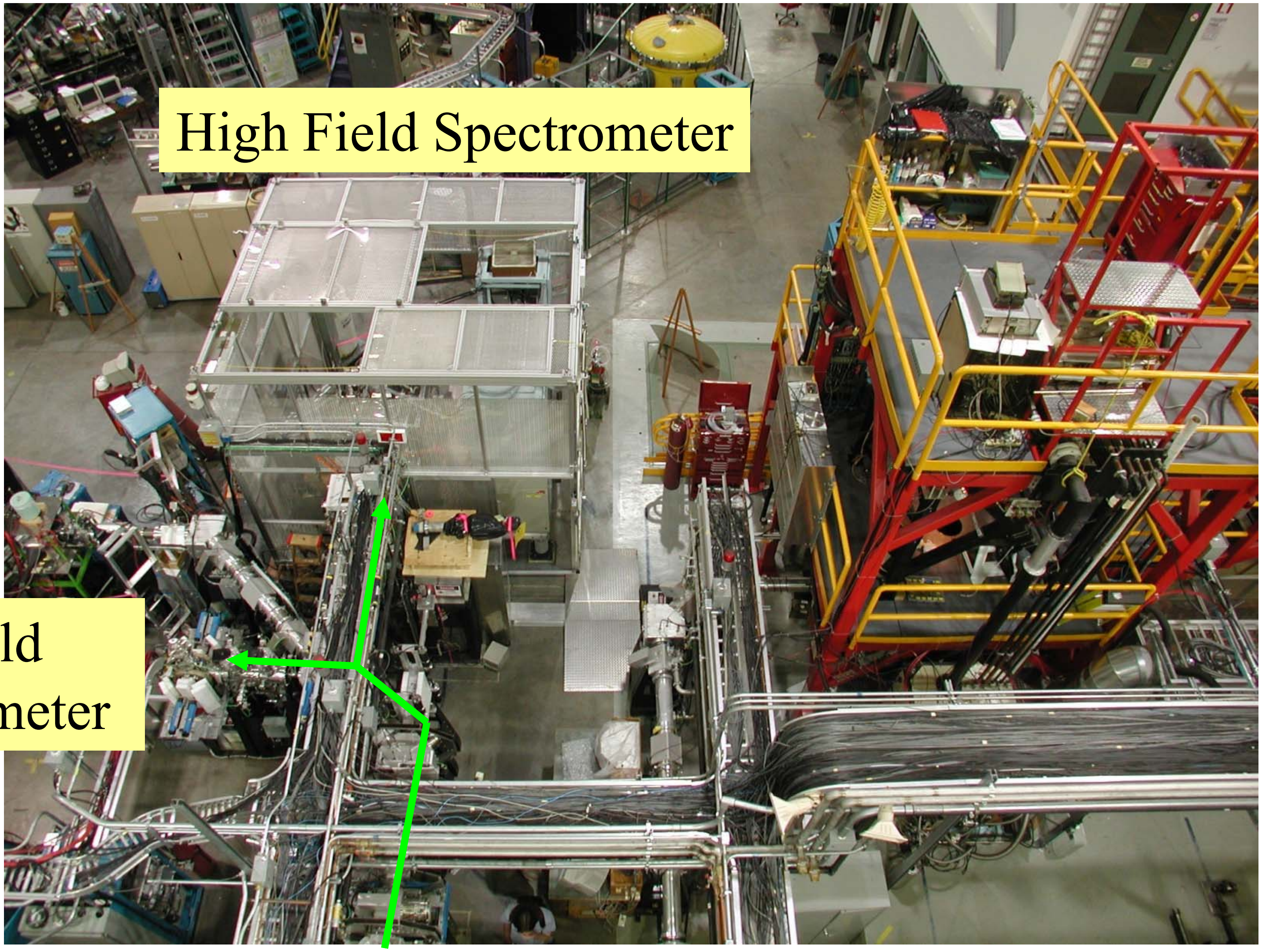
- Coupling of use of radioactive beams (nuclear) for Material science
- (Otto Hauser brought Rob Kiefl to the table at Traps Workshop)
- Presently uses ^{8}Li (and ^{9}Li) beams, 10^{9}/s (could use other beams also)
- Remember $T_{1/2}(^{8}\mathrm{Li}) = 838$ ms !!!
- 30-60 keV,
- Polarized !!!
- Sample on HV platform to tune implantation depth
- Adjust temperature, B fields, RF
- Now there are 2 experimental stations
  - High field beta-NMR
  - Low field beta-NMR and zero field beta-NQR
- Detect ^{8}Li beta asymmetry
- Ideal for senstive probing of thin films
- Connects with μSR studies (very large user group)
- Brings many users to ISAC also

β-NMR Spectrometers at ISAC



- Optical pumping with a tuned laser is used to achieve ~70% of spin polarization.
- Electrostatic deceleration is used to control the depth of the implanted ions (2-500nm)

β-NMR Spectrometers at ISAC



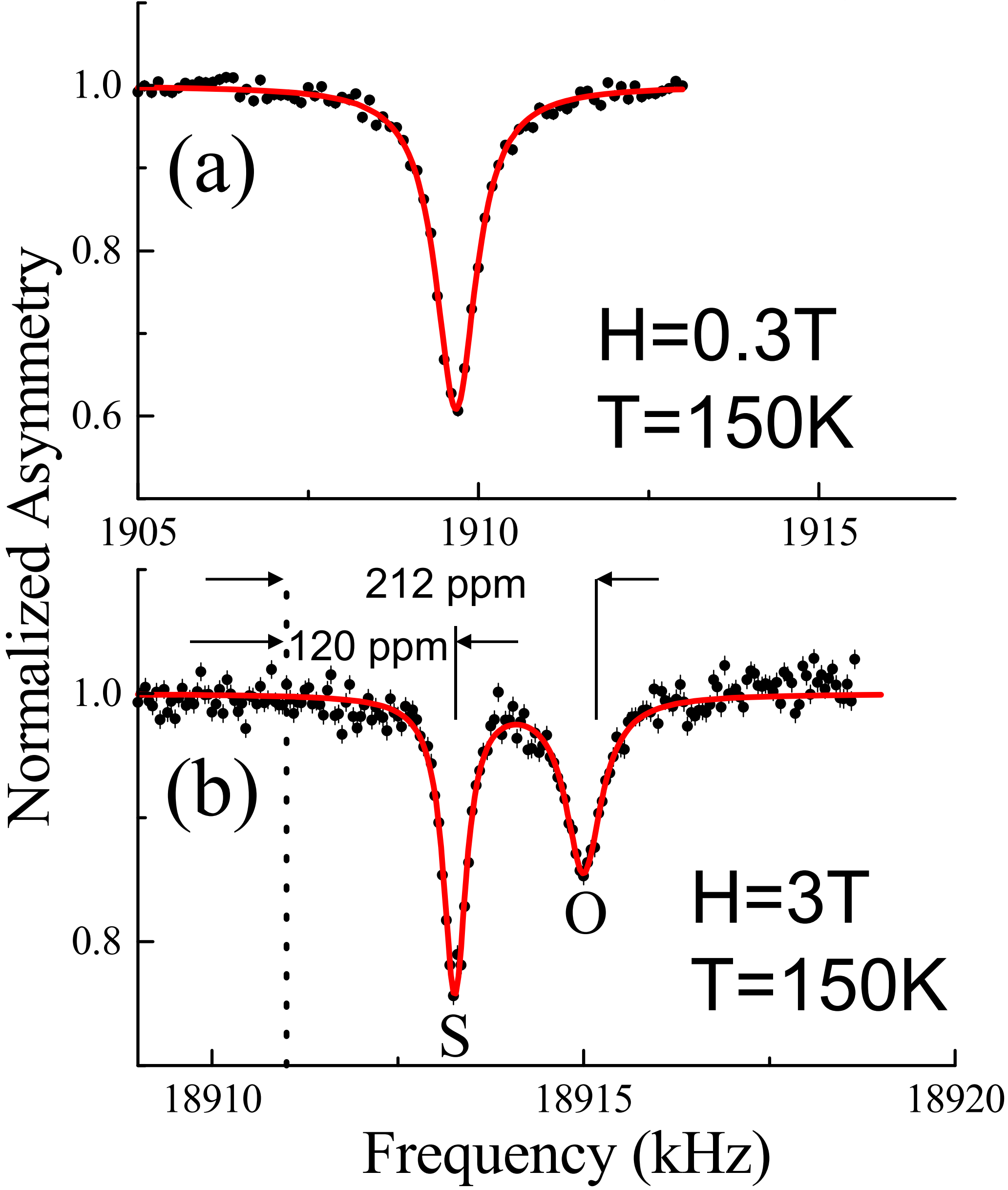
High Field Spectrometer

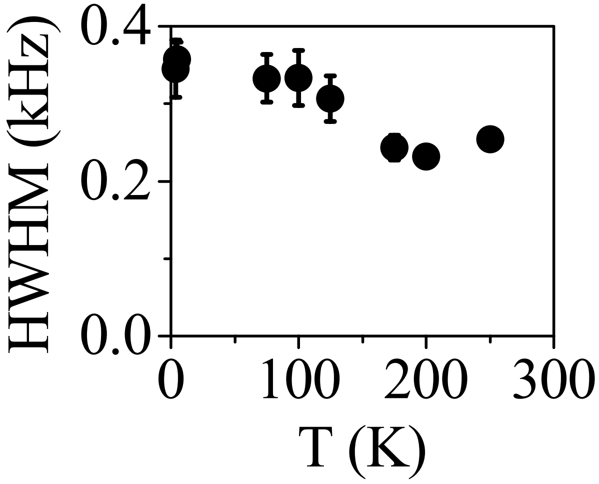
Low Field Spectrometer

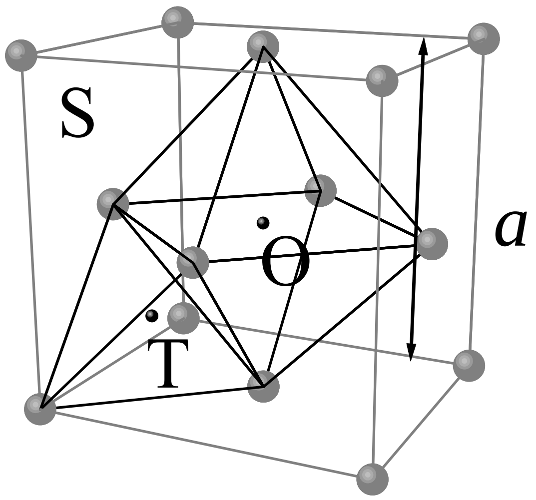
Polarizer

High Resolution β-NMR of ^{8}Li in Ag

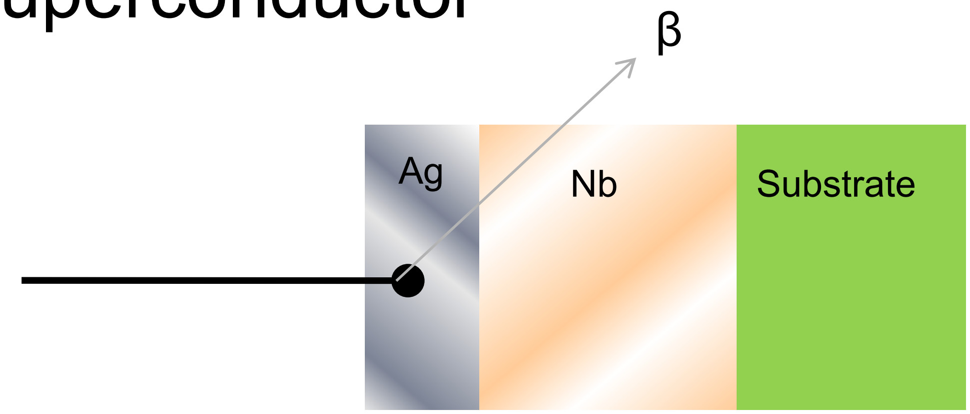
G.D. Morris et al, PRL 73, 15601 (2004).







Thin Film Ag on Nb Superconductor



- Thin Ag film on Nb surface
- Exhibits
“Proximity Effect”
Superconductivity

- How deep? Ongoing program

- G. D. Morris,
W.A. MacFarlane,
R. Keifl

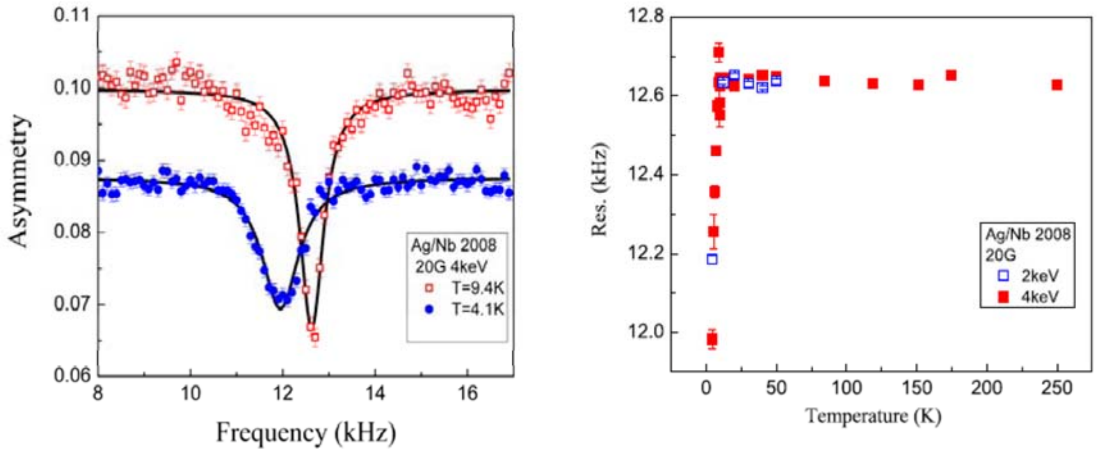
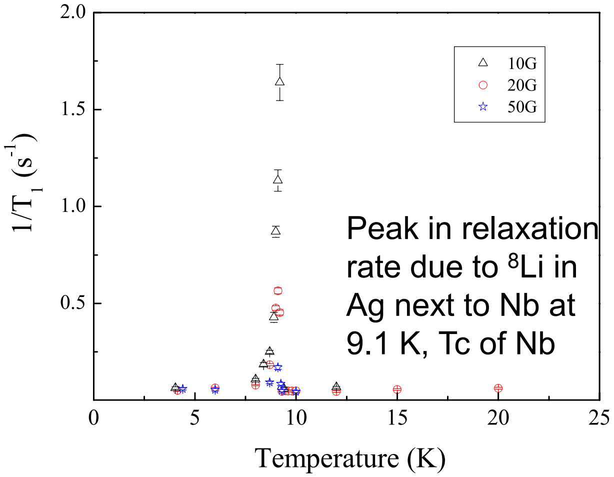


Fig. 1: Left: Resonance from ^{8}Li in Ag above and below the critical temperature T_{cNS} of the Ag(40nm)Nb(300nm) bilayer. Right: Resonance peak value versus temperature showing the diamagnetic shift below T_{cNS} in Ag.



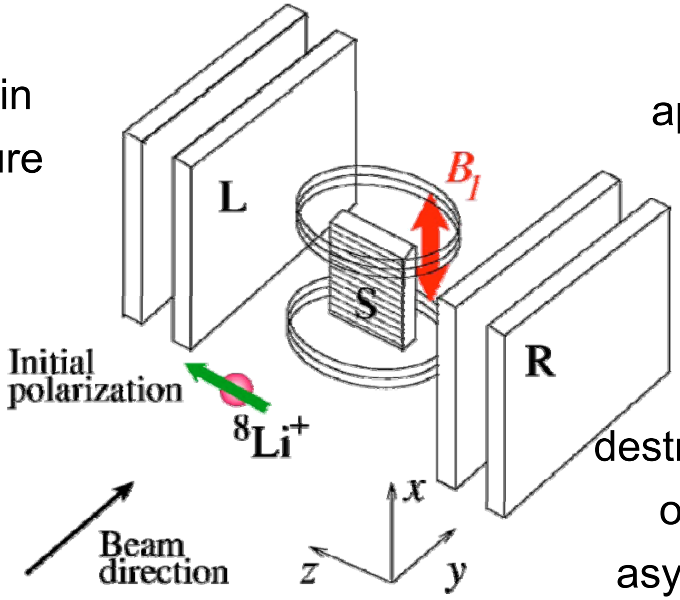
Peak in relaxation rate due to ^{8}Li in Ag next to Nb at 9.1 K, Tc of Nb

Measurement of the quadrupole moment of ^{9}Li and ^{11}Li

(M. Pearson et al.)

Spin polarised ^{8}Li and ^{9}Li ions implanted in insulator crystal ($SrTiO_3$) with cubic structure in zero magnetic field

ß decay asymmetry seen in Left and Right detector

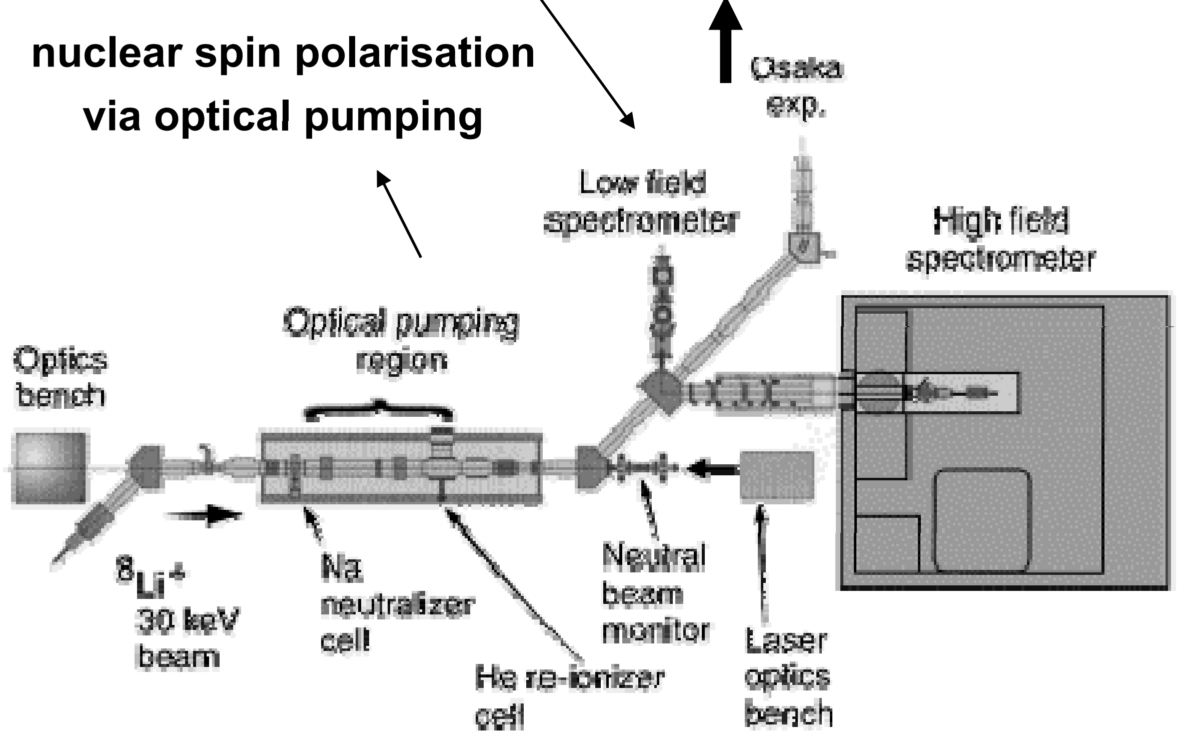


application of oscillating magnetic field B_1 destroys initial polarisation

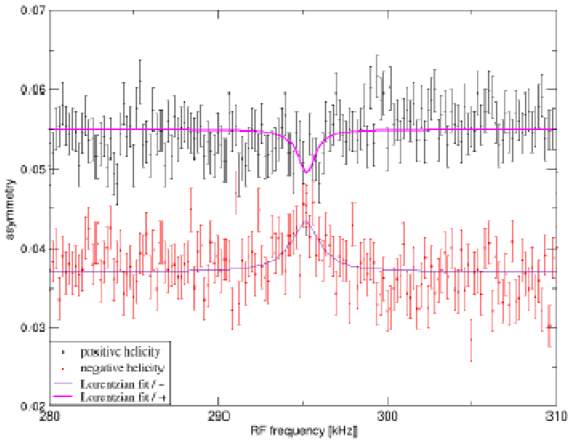
destruction of polarisation observed in loss of asymmetry in detectors

magnetic field set to zero

nuclear spin polarisation via optical pumping

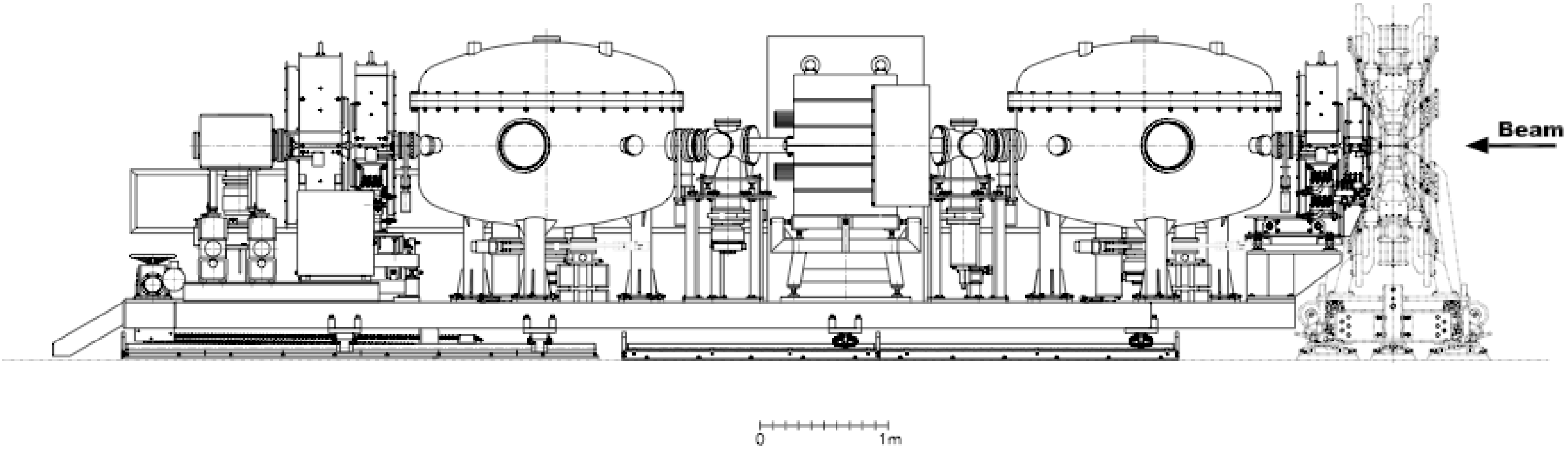


Preliminary:
^{9}Li: technique works
under analysis



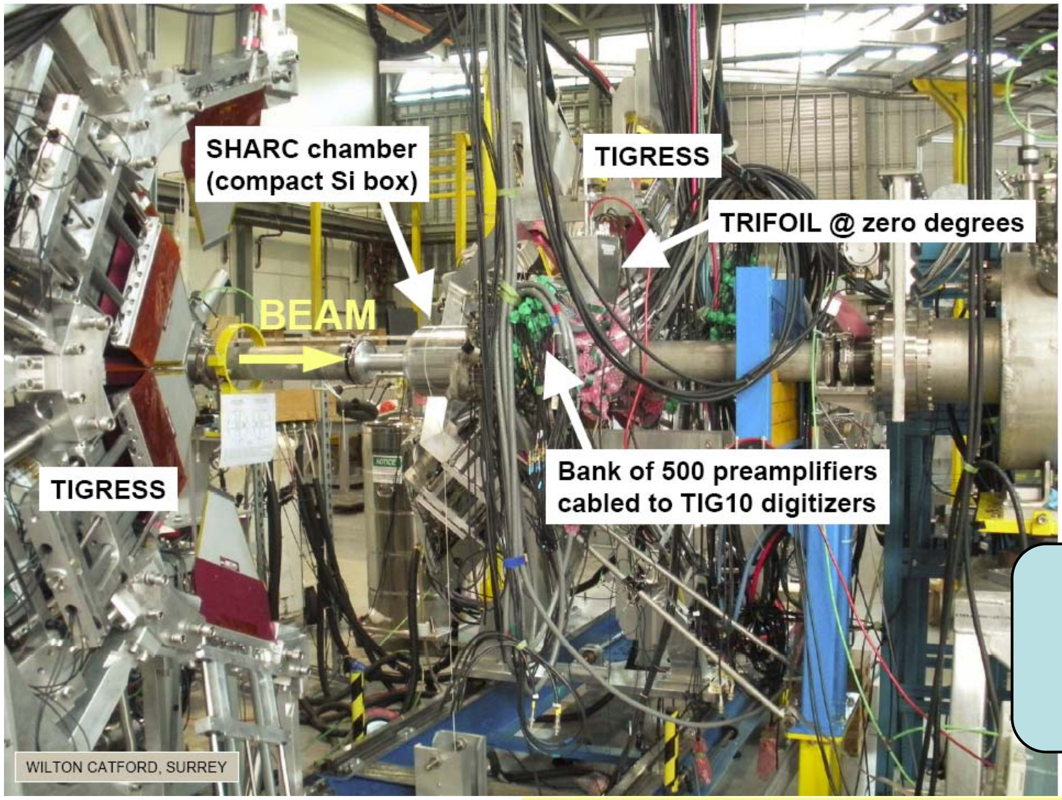
Future for ISAC

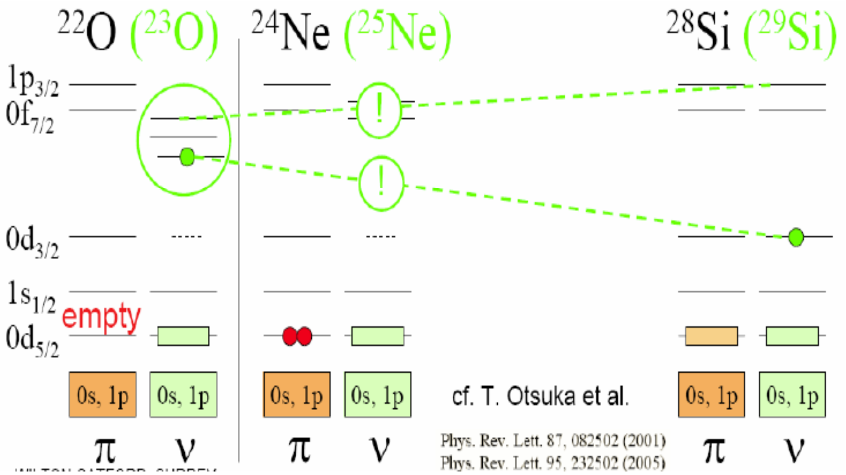
EMMA, the ElectroMagnetic Mass Analyser



Recoil Mass Spectrometer for ISAC-II
Project Leader: Barry Davids
Length = 9 m; 1st order mass resolving power = 500
Solid angle: ± 4˚ by ± 4˚ = 20 msr
M/q acceptance = ± 4%; Energy acceptance = ± 20%
Heavy recoil tagging in fusion-evaporation and transfer reaction spectroscopy
Applications: nuclear astrophysics and exotic nuclear structure
Commissioning in 2011

Probing the Transition to the Island of Inversion
TIGRESS & SHARC (C. Diget et al.)





particle-γ coincidences
experiment data under analysis
more planned for 2010

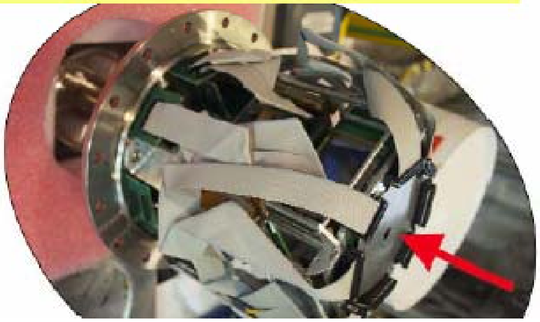
Nucleon transfer
by (d,p) at 5 MeV/u
at ISAC2

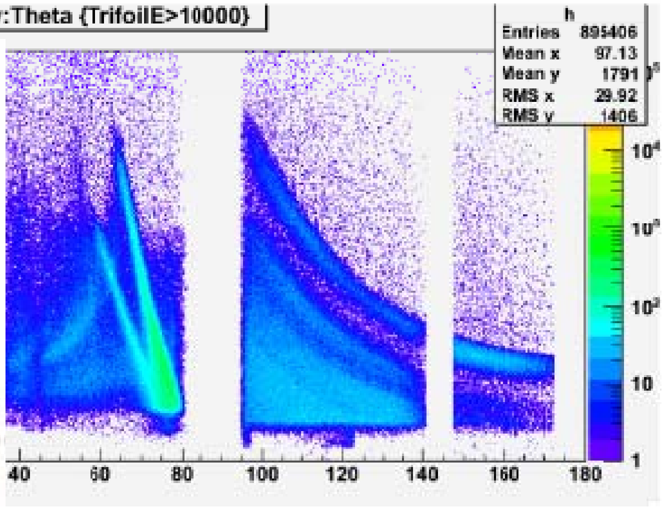
Prototype of new type of experiment for us – where the states are so close together in this odd-odd nucleus that we will need to GATE on gamma transitions in order to separate the different final states

At ISAC2 we will use the isotone of ^{24}Ne namely ^{25}Na as the projectile.

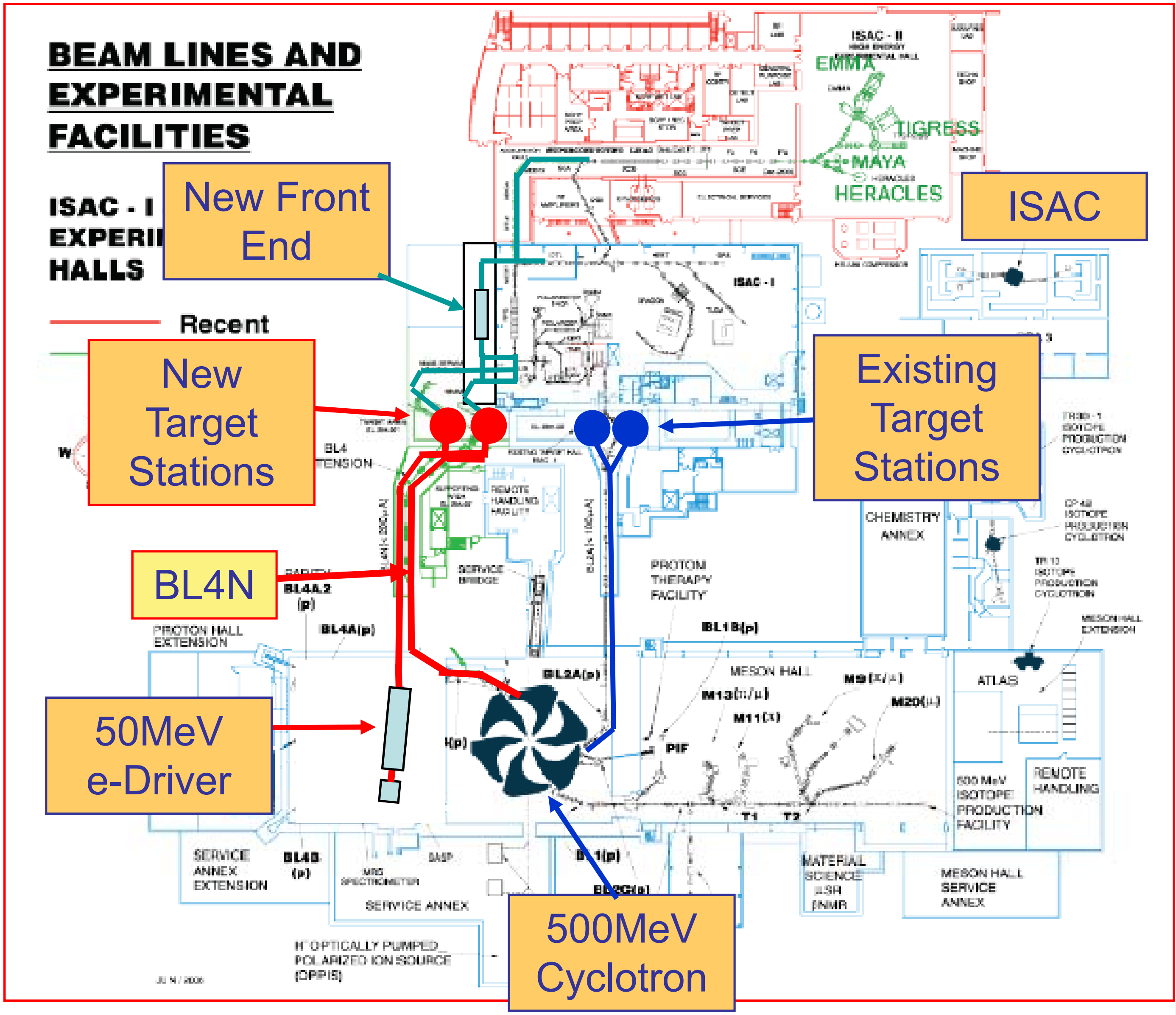
We aim to test the modifications to USD that have been used to reproduce the raised d3/2 level seen in ^{25}Ne, by measuring the p-n coupling states in ^{26}Na.

The experiment will use 10^6 pps ^{25}Na at 5.00 MeV/u.



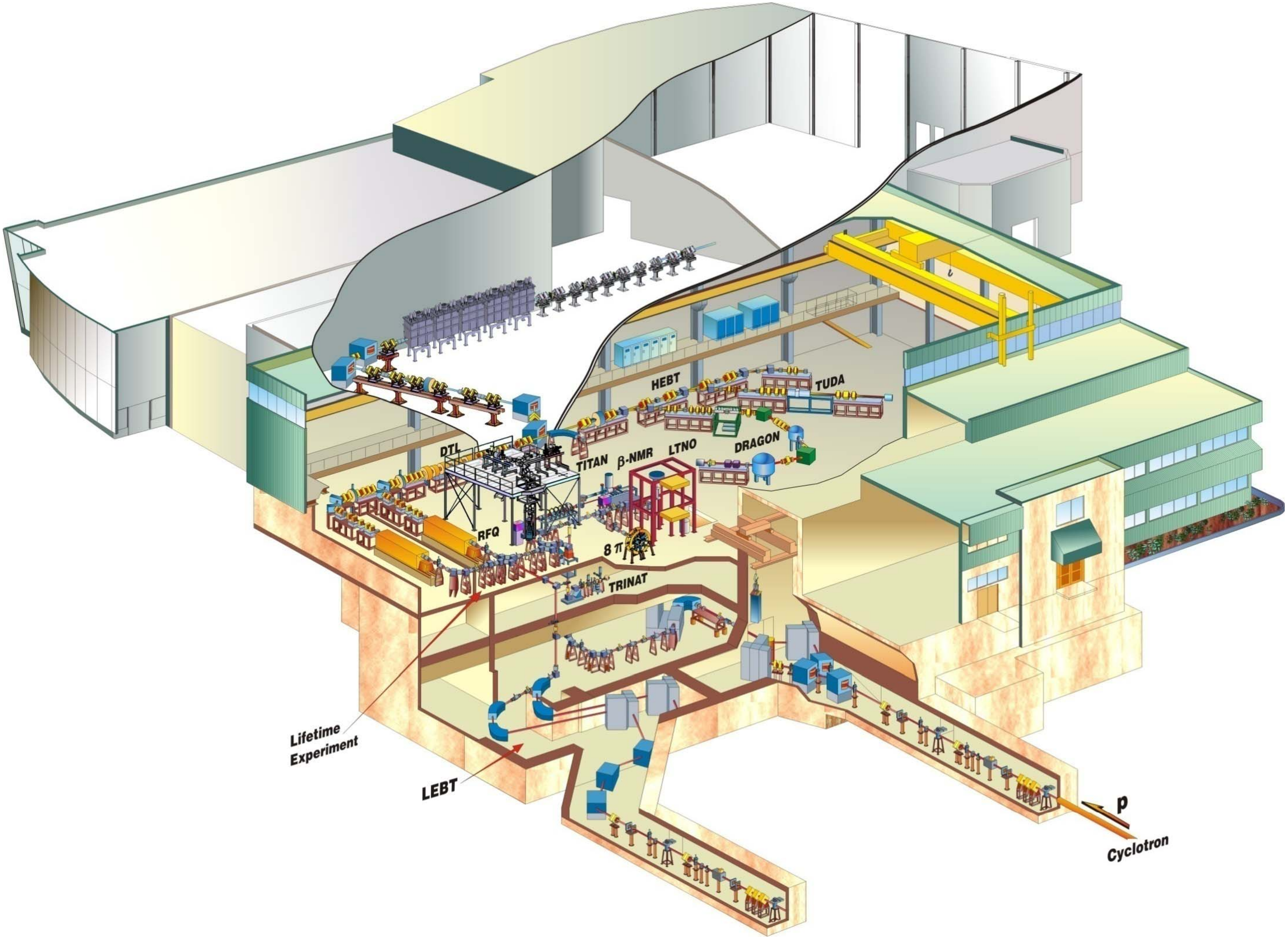


The future site map of TRIUMF



Proposal:

- **BL4N is proposed to deliver 500-MeV protons to two actinide target stations for beam production**
- **Take advantage of the shielded and unused proton hall to add a 50-MeV electron driver to supply electrons to the new target area via a separate beamline**
- **Develop new ISAC front end to permit three simultaneous RIB beams (two accelerated)**
- **E-linac CFI funded (awaiting matching funds)**


HEBT
TUDA
DRAGON
DTL
TITAN
β-NMR
LTNO
RFQ
8 π
TRINAT
Lifetime Experiment
LEBT
p
Cyclotron

The People (some)

Alan Astbury, Alan Shotter and Erich Vogt
Paul Schmor
Marik Dombsky – ISOL Targetry
Pierre Bricault- ISOL ion sources and other components
Lothar Buchmann (w Dick Azuma, Jim King) – Reactions with RB for Astrophysics
Jack Beveridge – Shielding and initial layout
Harvey Schneider (and Bob Laxdal and PB) – RFQ and LINAC
Otto Hauser (and Peter Jackson and John Behr) – TRINAT
Dave Hutcheon – DRAGON (Technical aspects)
Gordon Ball – Nuclear Structure and, and, and
Rob Kiefl (Phil Levy,Gerald Morris)–Condensed Matter (with polarized ^{8}Li)
Jean Michel Poutissou – Science leadership and beam scheduling

Newer group
  Jens Lassen
  Jens Dilling
  Chris Ruiz
  Barry Davids
  Carl Svenson (and Greg Hackman and Paul Garrett)
  Matt Pearson

Entire TRIUMF staff (Engineers, Remote Handling Group, Technicians, Machinists, Draftspersons and Designers, etc…)

Concluding Remarks

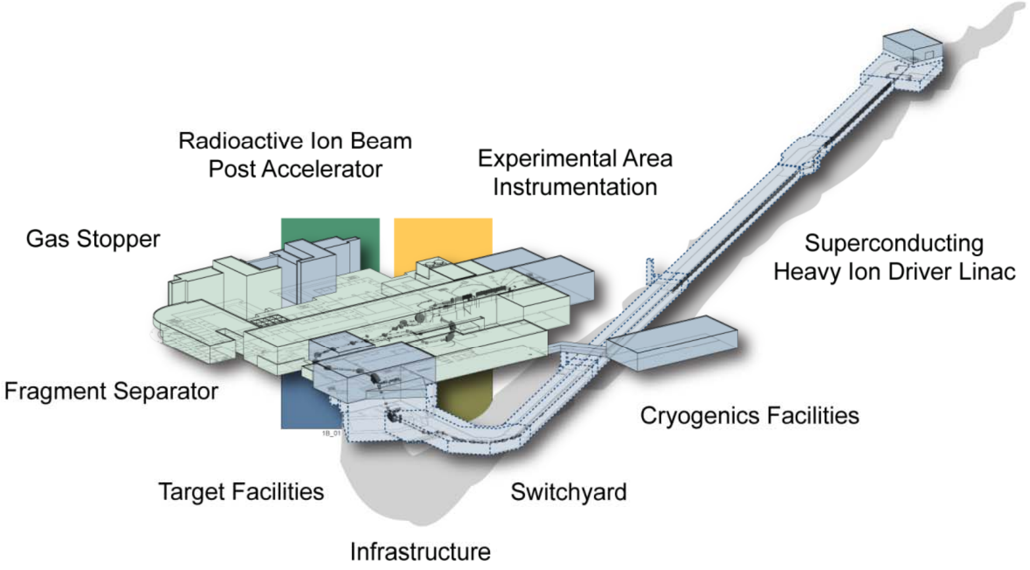
- ISAC is now a world class facility for nuclear astrophysics, nuclear structure studies, fundamental symmetries and condensed matter physics;
- Window of opportunity before FRIB, FAIR and others;
- Needs constant development of new radioactive and stable heavy ion beams and with higher intensities;
- First class training ground for students and post-docs;
- Bright future with existing world class, unique facilities;
- Exciting forward looking 5 year plan;

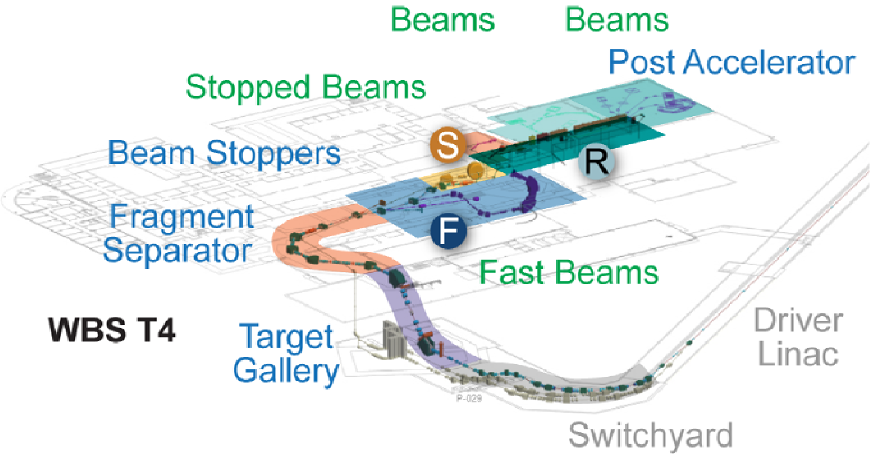
- BUT, should not lose sight of what got it here:

  - an excellent scientific, technical and professional staff (dedicated, open, cooperative, loyal, good will, creative)

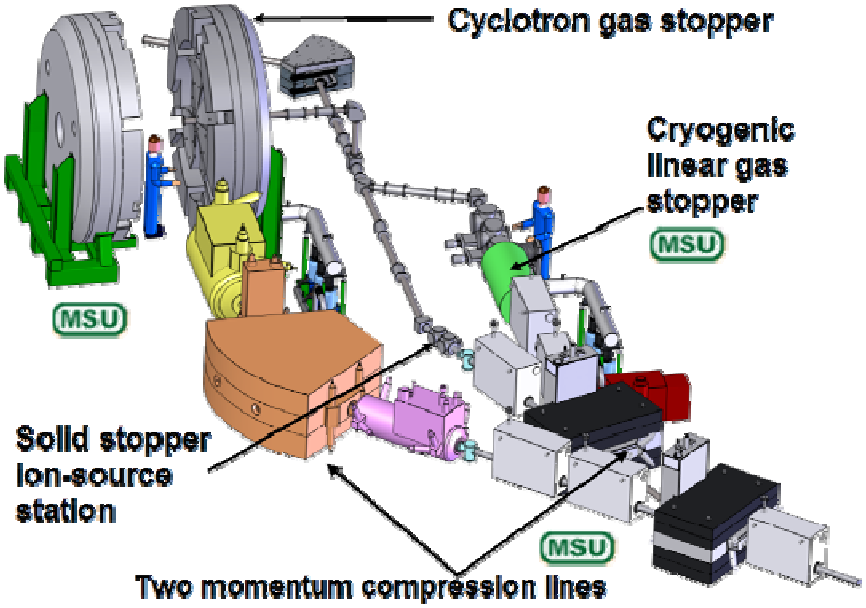
End of Slides

FRIB at MSU

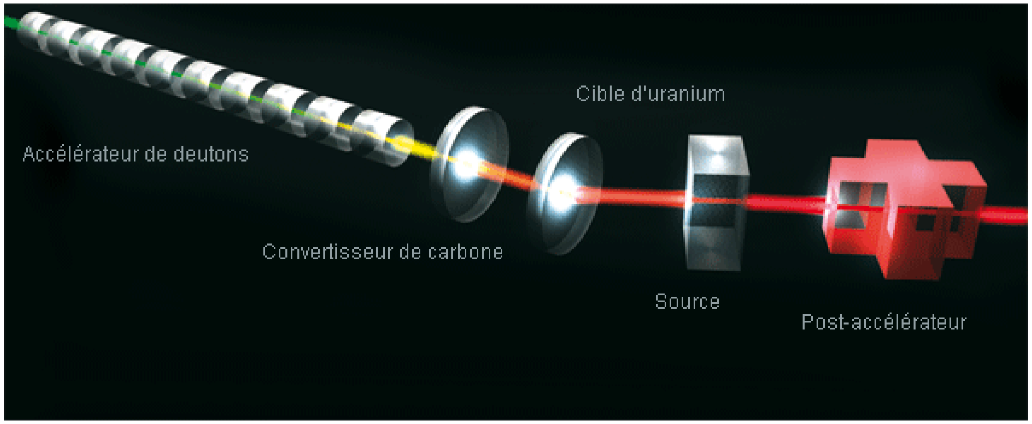


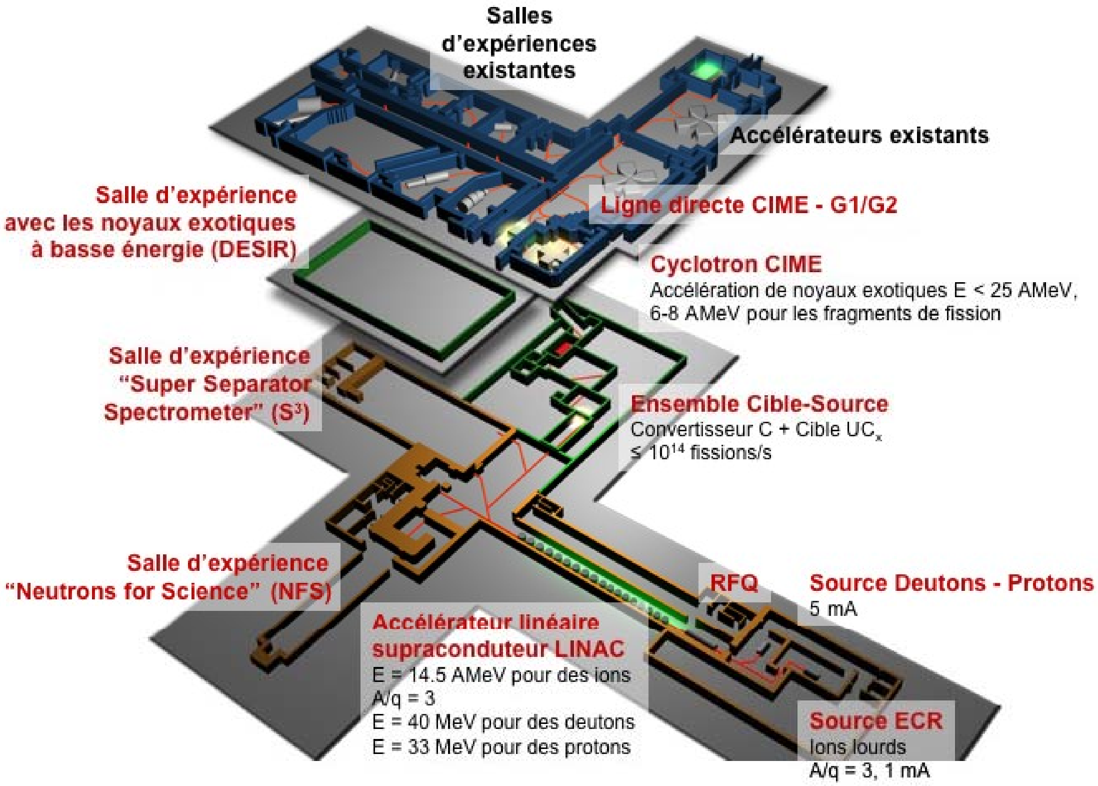


WBS T4



SPIRAL 2



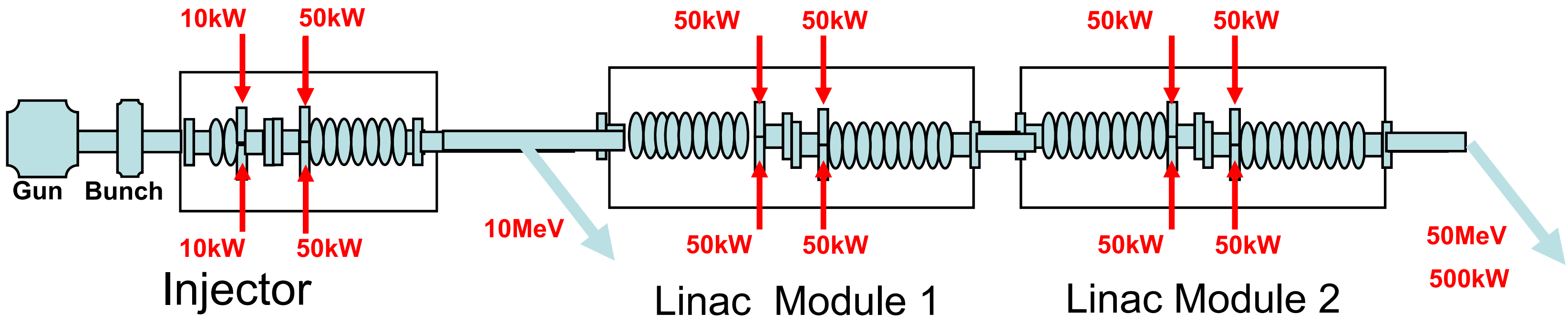


40 MeV ^{2}H → Converter

Neutrons → Uranium tgt

Fission → ISOL approach ??

E-linac: MW-class Superconducting Electron Accelerator at TRIUMF

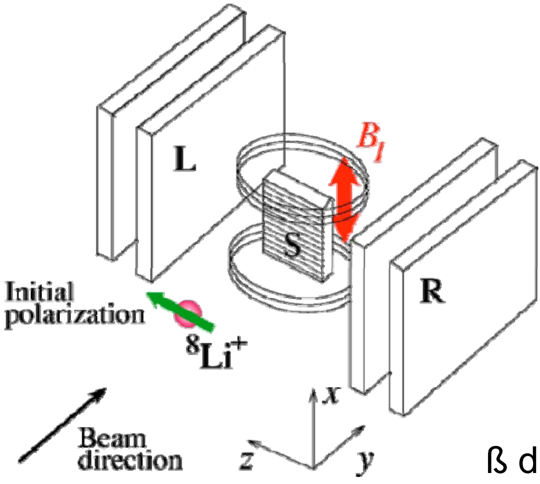


- A MW-class electron linac is a driver for photofission with rates up to 10^{14} fissions/sec.
- The present e-linac design concept, based on 1.3 GHz SRF CW operation, offers flexibility, possibility for expansion to other applications (Free Electron Laser, Energy Recovery Linac).

- Design parameters: 50 MeV, 10 mA, CW operation.

β-NMR probes phase changes

- ^{8}Li and ^{9}Li beams, 10^9/s
- 30-60 keV,   Polarized
- Sample on HV platform to tune implantation depth
- Adjust temperature, B fields, RF
- Two experimental stations
    - High field beta-NMR
    - Low field beta-NMR and zero field beta-NQR
- Detect ^{8}Li beta assymetry
- Ideal for senstive probing of thin films
- Connects with μSR studies



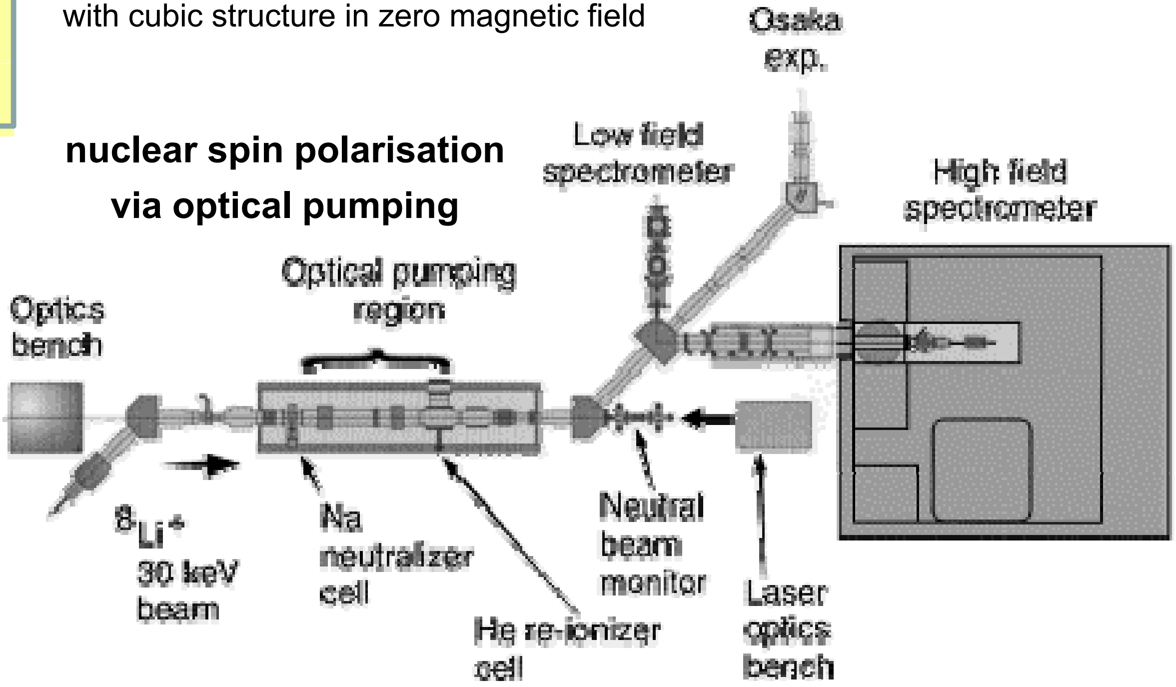
application of oscillating magnetic field B_1 destroys initial polarisation

destruction of polarisation observed in loss of asymmetry in detectors

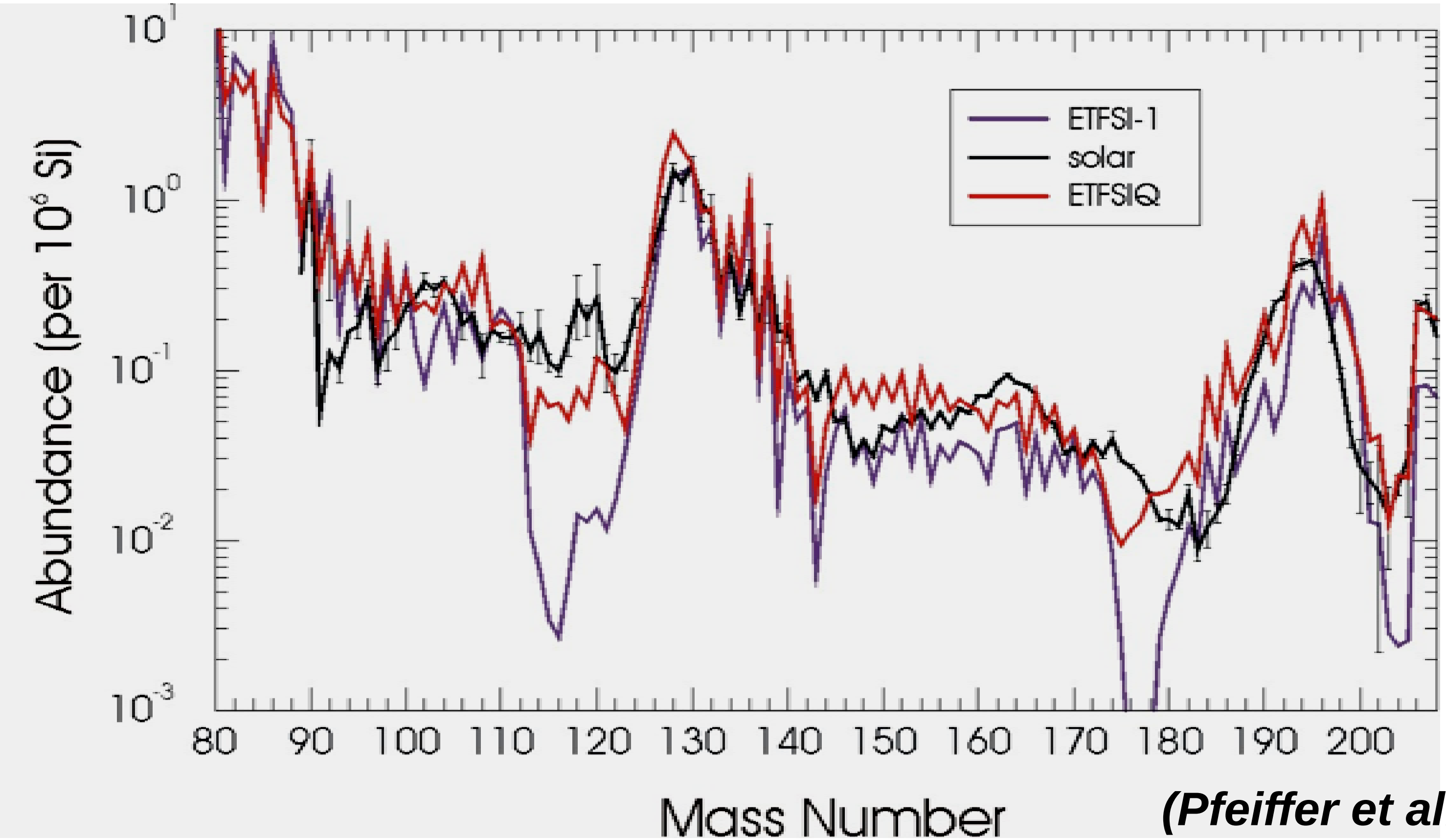
ß decay asymmetry seen in Left and Right detector

Spin polarised ^{8}Li and ^{9}Li ions implanted in insulator crystal ($SrTiO_3$) with cubic structure in zero magnetic field

nuclear spin polarisation via optical pumping



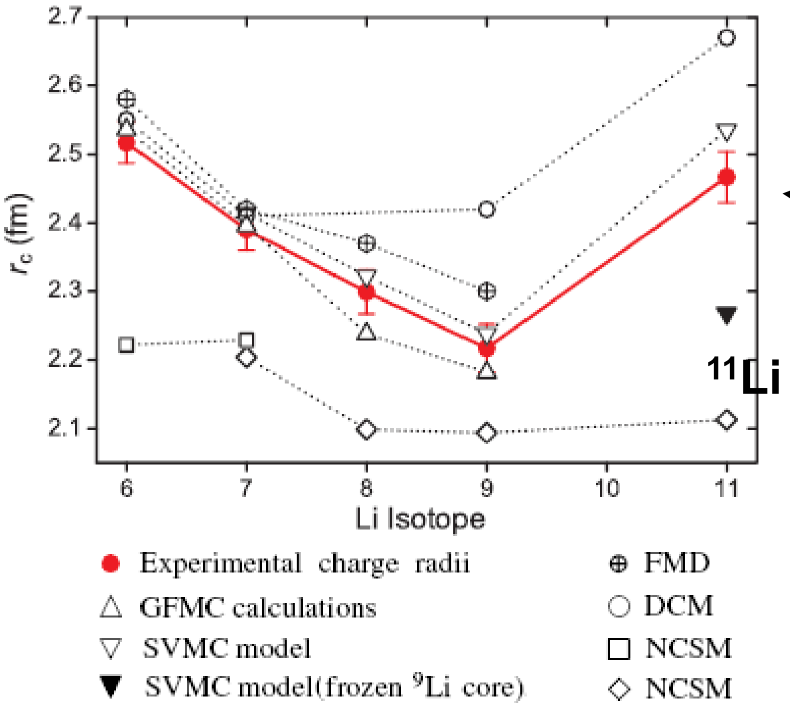
The r-process and Shell Quenching



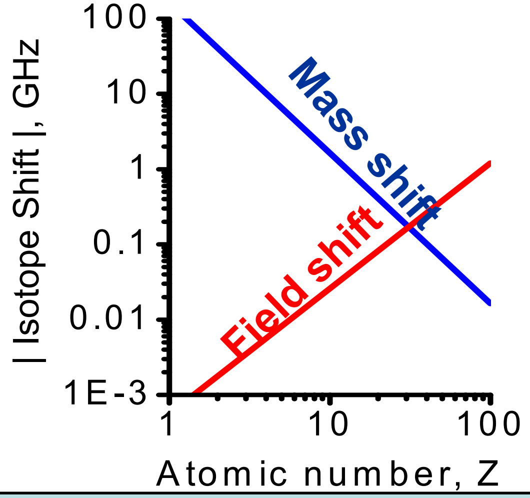
(Pfeiffer et al. 1997)

- Observed solar abundances of Cd/In/Pd, Hf/Ta/W not compatible with nuclear shell model!
- Quenching shell gaps in calculations gives answer closer to abundances

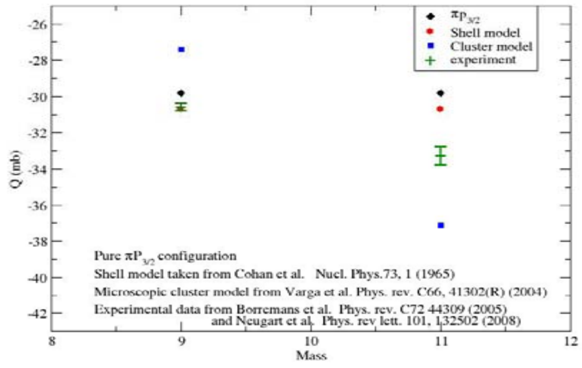
Charge radius determination @ ISAC



- Isotope shift measurements: ToPLiS collaboration @ ISAC measured laser frequency shifts for the lithium isotopes
- G. W. Drake (Windsor) **PRL. 100, 243002 (2008)** atomic theory calculations for the mass shifts => extract the charge radius
- Isotope shift = modification of electron binding energy =Mass Shift (mass effect)
  + Field shift (finite size of nucleus)



Curent status of the quadrupole moments of ^{9,11}Li



Pure $\pi P_{3/2}$ configuration
Shell model taken from Cohan et al. Nucl. Phys.73, 1 (1965)
Microscopic cluster model from Varga et al. Phys. rev. C66, 41302(R) (2004)
Experimental data from Borremans et al. Phys. rev. C72 44309 (2005)
and Neugart et al. Phys. rev lett. 101, 132502 (2008)

Mass & QM measurements
& needed!

ISAC: The First 10 Years

- What is ISAC
- What is its place in the World
- How did it start
  - Proposal in 1985
  - TISOL (10 year for learning)
    - Key Studies at TISOL
  - Buiding the facility
    - Remote Handling and Shielding
    - The Target and Beam Production
    - Key Components
      - The RFQ Accelerator
      - The High Resolution Mass Anayzer
    - ISAC II
- Science in the First 10 Years
  - Nuclear Astrophysics
    - DRAGON
    - TUDA
    - Other studies (Ne)
  - Fundamental Physics
    - TRINAT
    - Superallowed Beta Decay
  - Condensed Matter Physics
    - Beta NMR and Polarized ^{8}Li
  - Nuclear Physics and Structure
    - The 8 Pi
    - TITAN
    - TIGRESS
    - Li11 Charge Distribution

- What does the future hold?
- Concluding remarks (people, creativity, good will and cooperation)

Planned Experimental Facilities and Beams

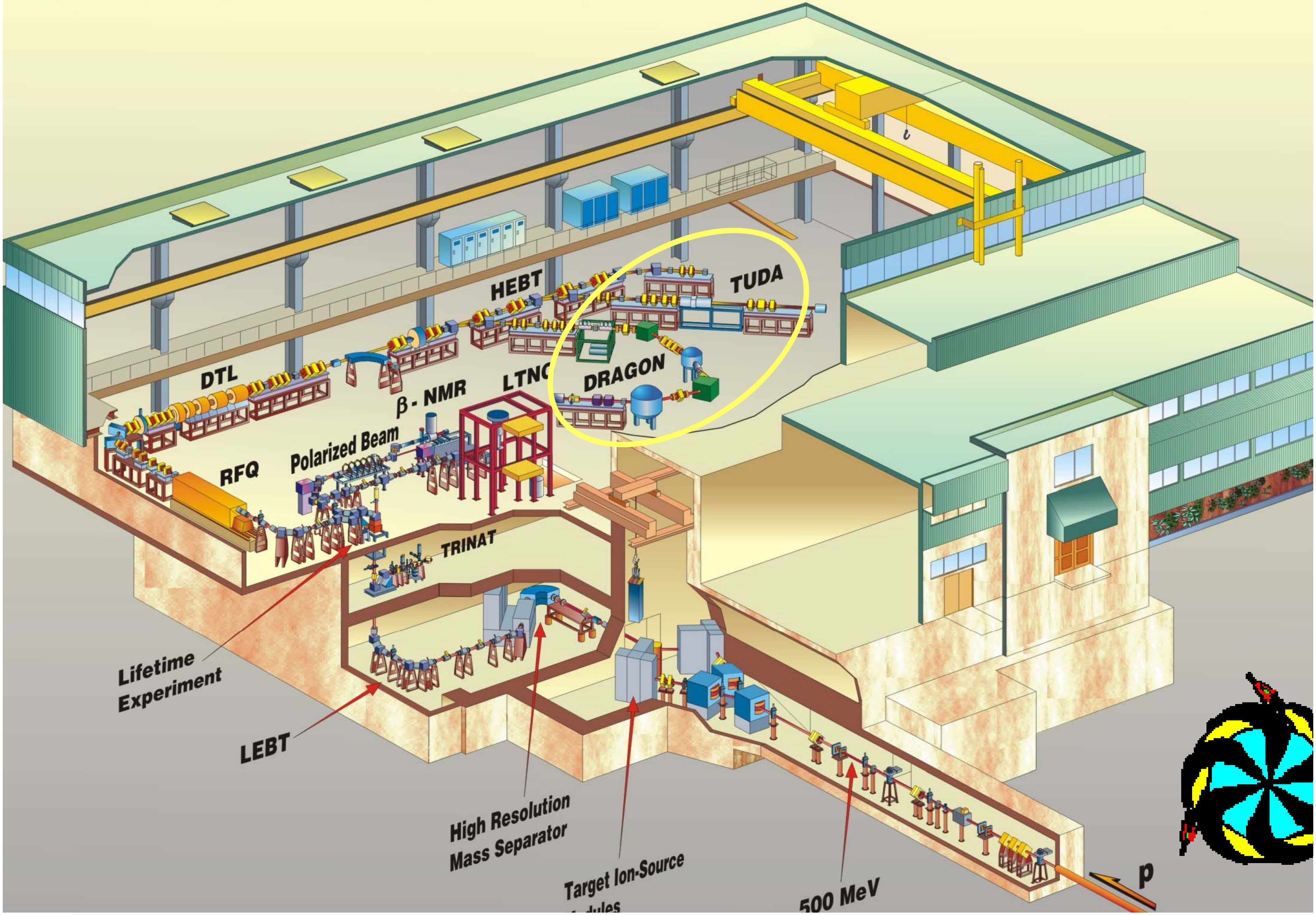
- EMMA

- TIGRESS (Completed)

- Actinide Targets (on a regular basis)
  - TRINAT and FrPNC
  - Radon EDM
  - r-process masses for astrophysics

- Second Production Target System including   e-LINAC

ISAC at TRIUMF



The TRIUMF-ISAC Radioactive Beams Facility

- ISAC I Project proposed in 1985; funded in 1995 (5 year plan)
- RB Production by the ISOL Method (500 MeV p^+)
- RB Accelerated using LINACS (0.15 – 1.5 MeV/u): ISAC I
- Two ISAC 1 Experimental Areas (LEBT and HEBT)
- ISAC II funded in 2000;

- Major Technical Milestones
  - 1998 – First RB beam (^{38m}K) to TRINAT
  - 2000 – First physics (^{74}Rb lifetime with high precision)
  - 2001 – TUDA and DRAGON perform RB experiments;^{21}Na
  - 2002 - 8π and β-NMR perform physics
  - 2003 - TITAN and TIGRESS Funded; ISAC II bldg. opened
  - 2004 - ECR used for exp.; CSB tested; ^{26}Al beam;
    (high power target, ^{11}Li; laser ion source)
  - 200X – ^{26g}Al exp., ^{11}Li CSD done, + many other exps.

Radioactive Beams at TRIUMF-ISAC

The ISOL Method

- 500 MeV protons onto thick target
- Spallation, fragmentation, (fission) reactions
- Have used Nb, Ta, SiC, TiC, CaO, $CaZrO_3$, (ZrC)
- Intensities up to 150 μA possible **(now 100 μA)**
- Products diffuse out at high temperatures
- Species ionized in heated surface and laser ion sources;
  ECR (2004, revised 2008); FEBIAD(2006)
- Beams delivered to ISAC II (2006-7)
- Successfully tested uranium (actinide) target 2008

Some Beam Intensities at Yield Station

^{8}Li	(Ta)	8 x 10^{8} pps
^{11}Li	(Ta)	4 x 10^{4} pps
^{21}Na	(SiC)	**9.9 x 10^{9} pps**
^{26g}Al	(SiC)	**1 x 10^{10} pps**
^{74}Rb	(Nb)	1.3 x 10^{4} pps
^{79}Rb	(Nb)	4.6 x 10^{9} pps
^{160}Yb	(Ta)	8.4 x 10^{9} pps

M. Dombsky TRIUMF
www.triumf.ca/people/marik/