Nuclear Physics Tools for the Study of Molecular Ions

INT24-1

March 6, 2024

A. Galindo-Uribarri

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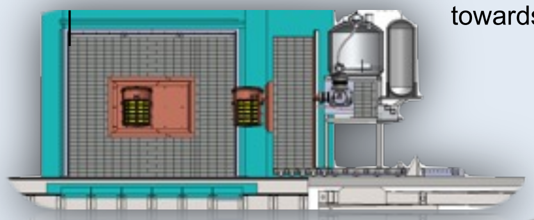
Outline

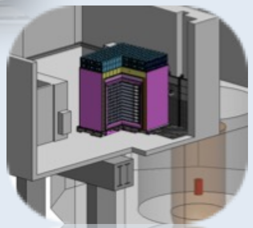
- Multidisciplinary research and challenges
- Signatures of New Physics
- Nuclear Physics Tools applied to the study of Atoms and Molecules (and back)
- Molecular ions (positive and negative)
- Simple molecules (discovery of $^{12}CH_2$++ and ^{13}CH++ and others)
- Clusters
- Actinides

Current interests in ν science

- Experimentally determine the fundamental properties of neutrinos and their interactions with matter
- Develop the best tools and detector technologies to support neutrino research.
- Develop neutrino applications in nuclear science and security.

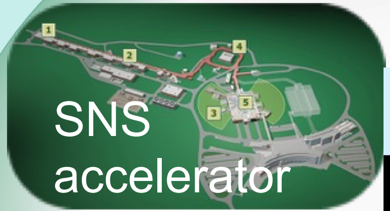


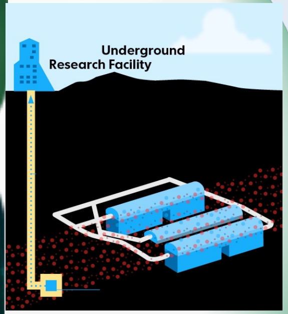
LEGEND-
towards 1 tonne ^{76}Ge experiment

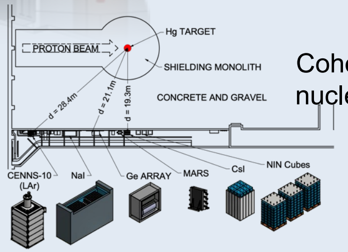


PROSPECT-
A Precision Reactor Neutrino Oscillation and Spectrum Experiment at the 85MW HFIR

Isotope Program:
Stable and Radioactive-
New capabilities

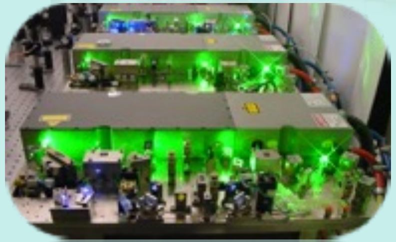






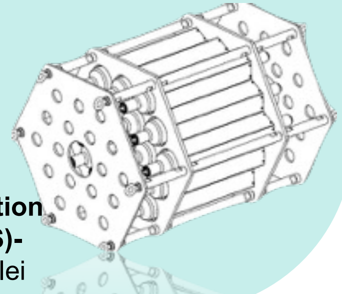
COHERENT-
Coherent elastic neutrino-nucleus scattering at SNS

Ultra Sensitive Analytical Techniques-
AMS
RIMS
NAA



Dark matter-
detectors technology

Quantum Information Science-
Machine Learning



Modular Total Absorption Spectrometer (MTAS)-
β-decays of n-rich nuclei

ORNL/UTK Students

High efficiency laser resonance ionization of plutonium
Science Reports (Nature) 2021

A Plutonium Needle in a Haystack

New results could significantly improve resonance ionization mass spectrometry ultra-trace analysis of plutonium isotopes.

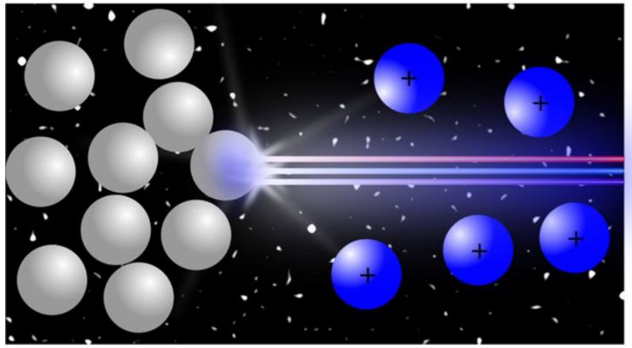


Image courtesy of Elisa Romero-Romero

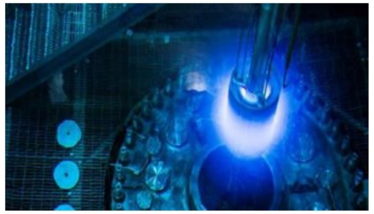
Resonance ionization mass spectrometry is a highly selective and sensitive technique for analyzing extremely small amounts of elements. It uses tunable lasers to ionize atoms of the desired elements.

DOE/NP

Elisa Romero

Highlights

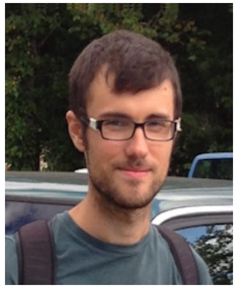
Final Measurement of the 235U Antineutrino Energy Spectrum with the PROSPECT-I Detector at HFIR
PRL 2023



PROSPECT Characterizes the Footprint of Neutrinos

Experiment at Oak Ridge National Laboratory's High Flux Isotope Reactor precisely measures the antineutrino energy spectrum.

DOE/HEP



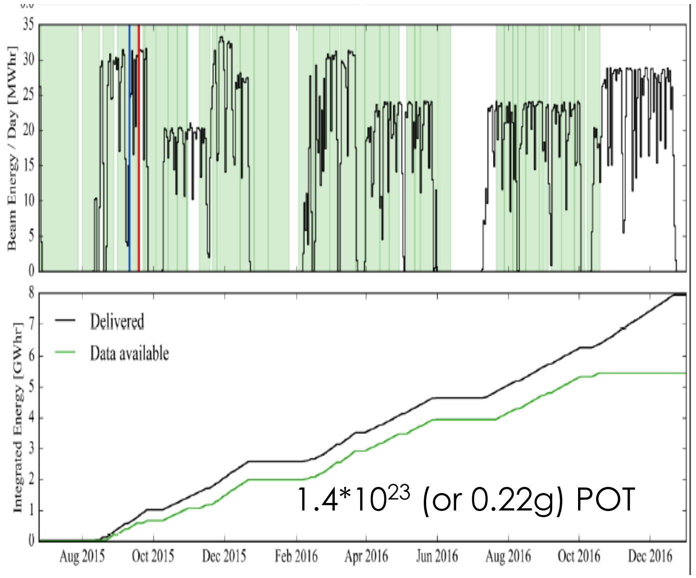
Blaine Heffron

Jeremy Lu

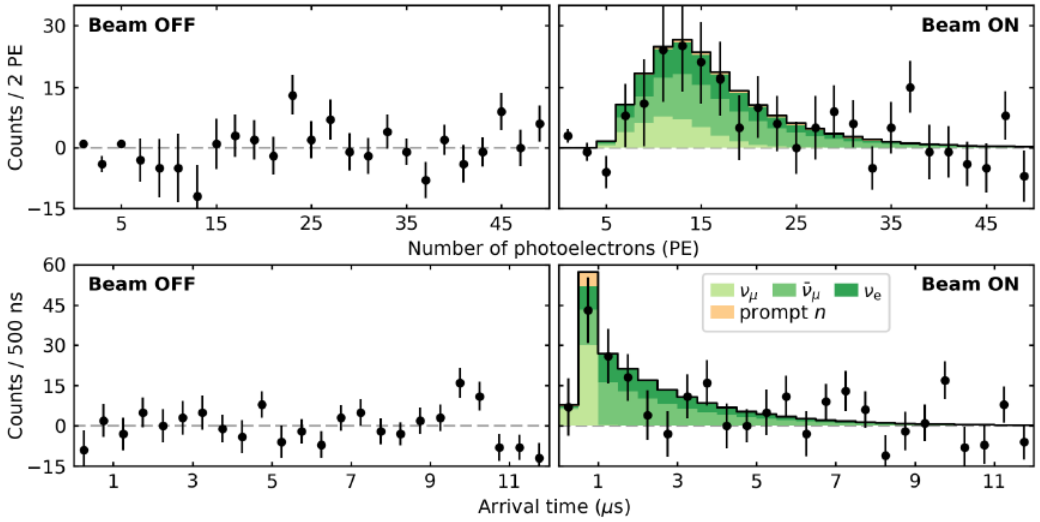
Diego Venegas

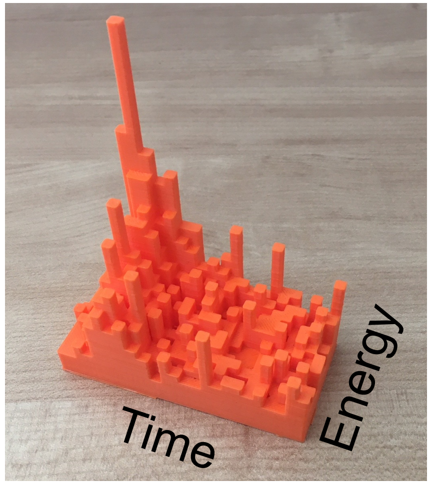
First Detection of CEvNS

Hand held neutrino detector



16 Month of data

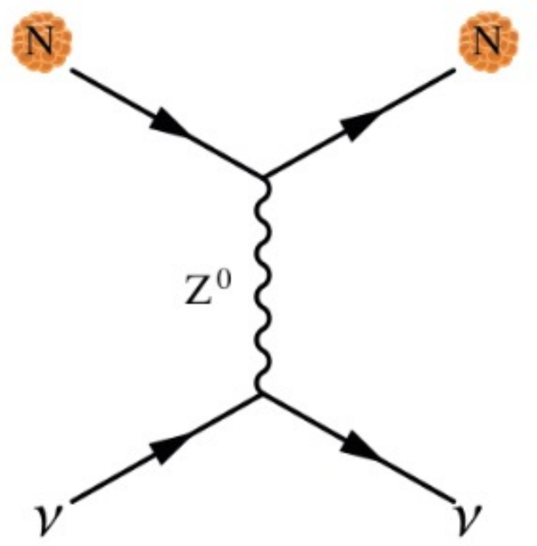




Coherent Elastic neutrino-Nucleus Scattering (CEvNS)

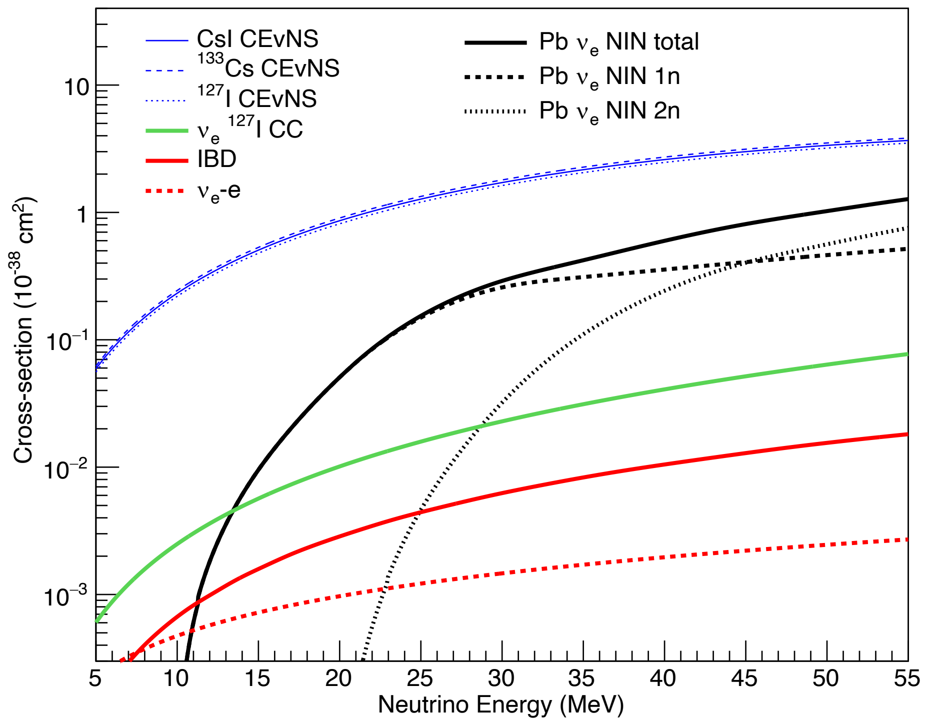
A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole;

coherent up to E_ν~ 50 MeV



D.Z. Freedman PRD 9 (1974)
Submitted Oct 15, 1973

V.B.Kopeliovich & L.L.Frankfurt
JETP Lett. 19 (1974)
Submitted Jan 7, 1974



CEvNS cross-section is large!

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1+\cos\theta) \frac{(N-(1-4\sin^2\theta_W)Z)^2}{4} F^2(Q^2) \quad \boxed{\propto N^2}$$

CEvNS cross section is well calculated in the Standard Model

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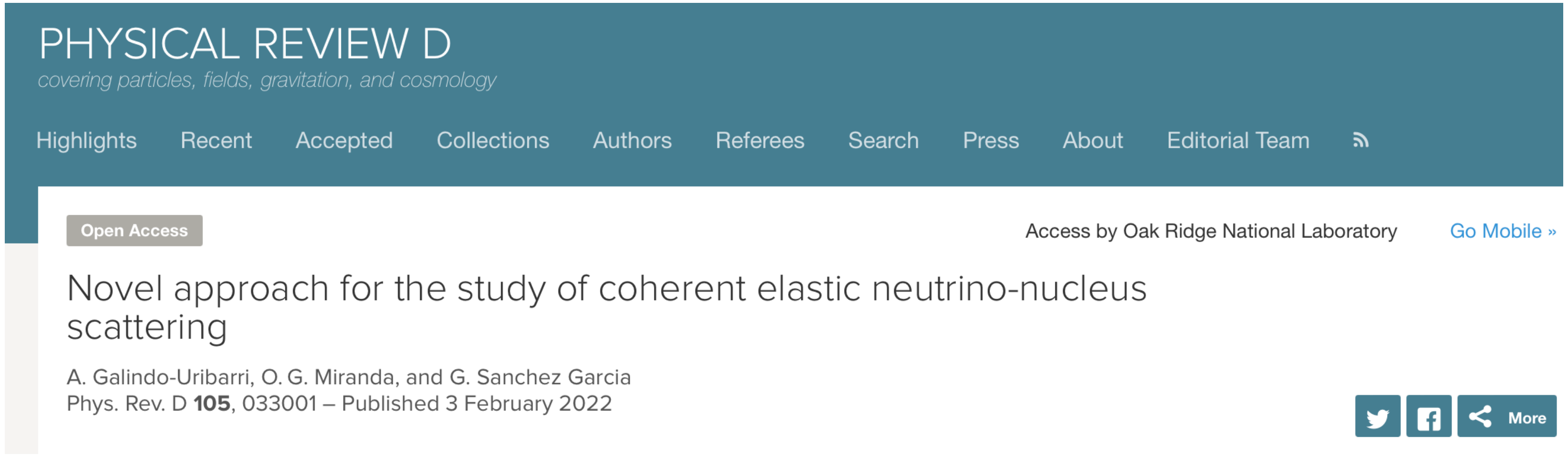
Novel Method for the study of coherent scattering

- Omar Miranda
- Gonzalo Sanchez

The Weizmann Award to the best doctoral theses carried out in Mexico by young researchers


PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology
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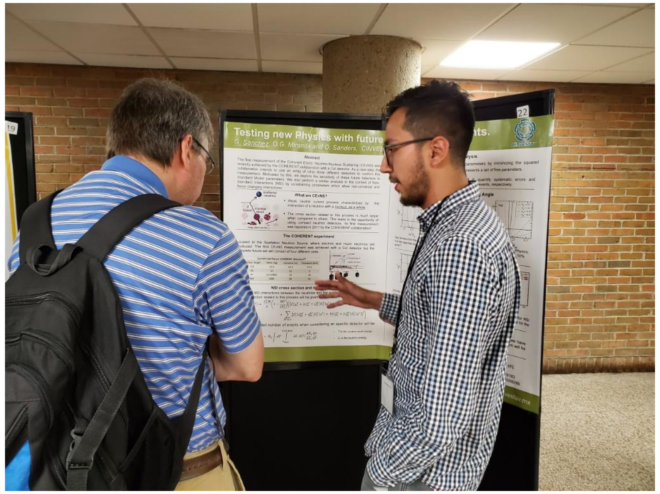
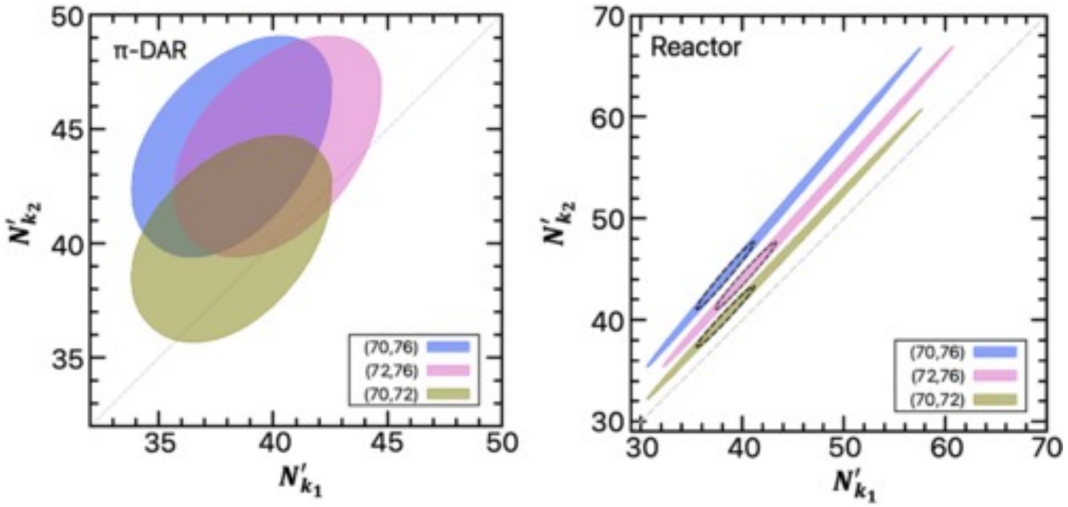
Novel approach for the study of coherent elastic neutrino-nucleus scattering
A. Galindo-Uribarri, O. G. Miranda, and G. Sanchez Garcia
Phys. Rev. D **105**, 033001 – Published 3 February 2022
More

Gonzalo Sanchez



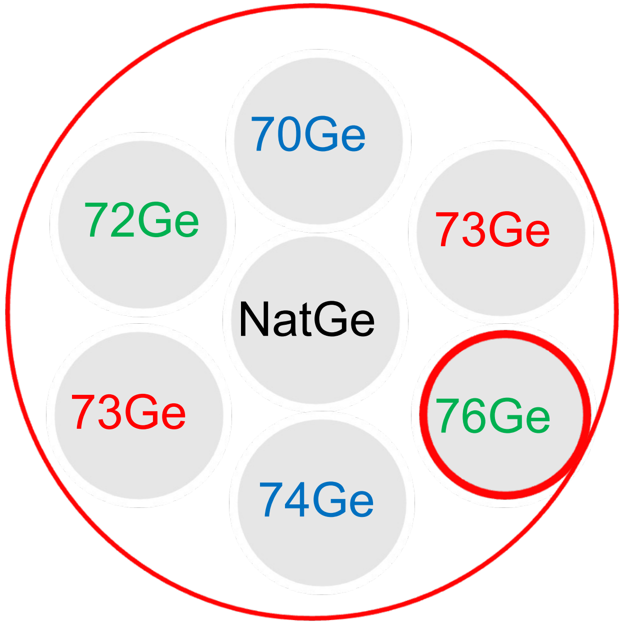
PHD, CINVESTAV (Mexico) 2022



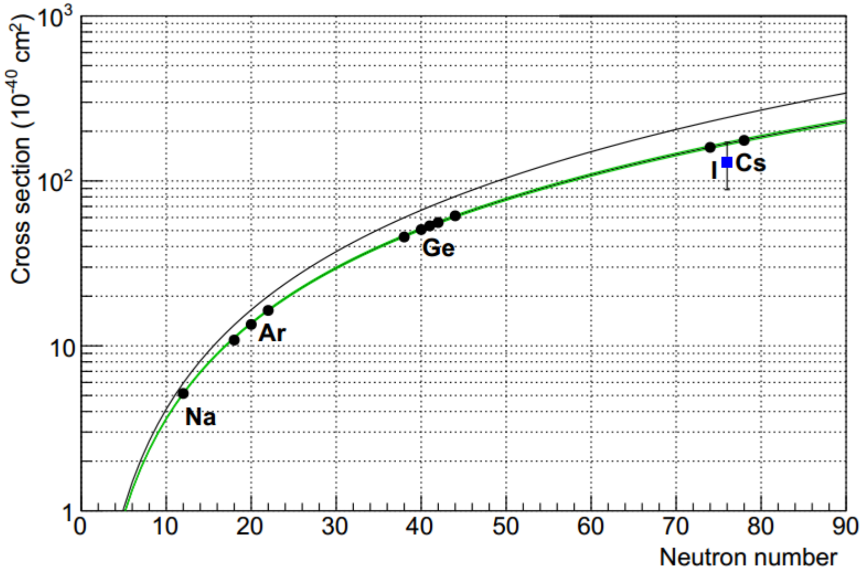
Oak Ridge National Laboratory

COHERENT scattering – Relative measurements

- Experiment with **identical** detectors
- **Different** isotopic composition
- Use **enriched** isotopes
- Perform **simultaneous** measurements
- **Cancelation of some systematic** errors
- Use **odd A** nuclei (Axial)

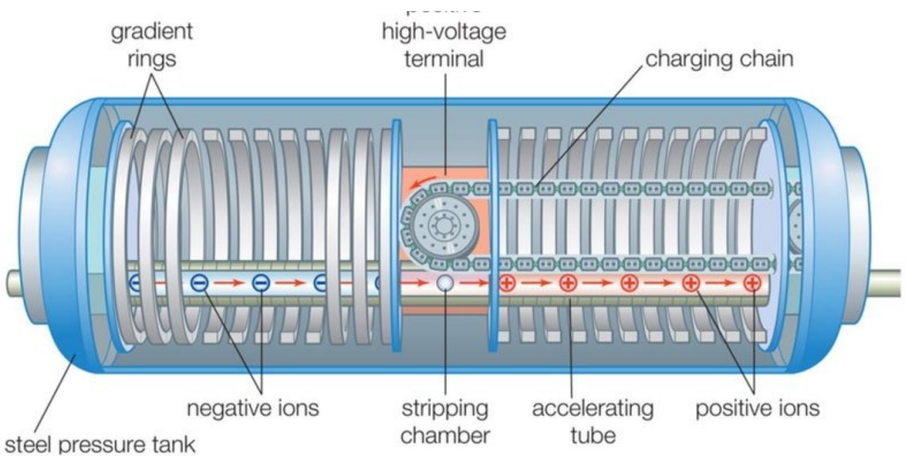


Mass	Natural Abundance	Decay Mode	Nuclear Spin
70	20.57%	STABLE	0+
72	27.45%	STABLE	0+
73	7.75%	STABLE	9/2+
74	36.50%	STABLE	0+
76	7.73%	STABLE	0+

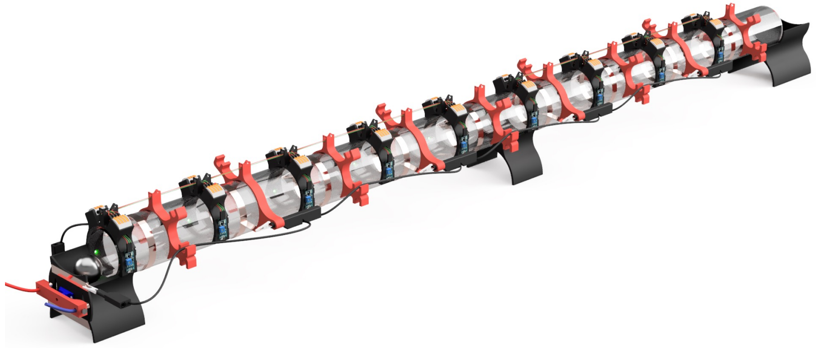


Nuclear Physics Tools - Accelerators

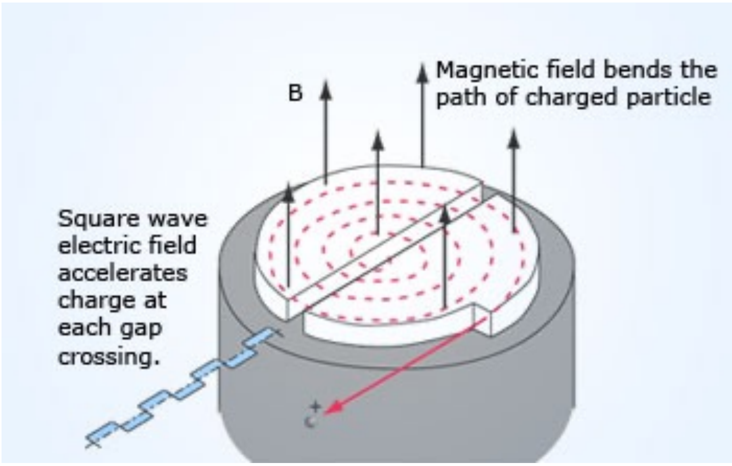
Electrostatic Tandem Accelerator



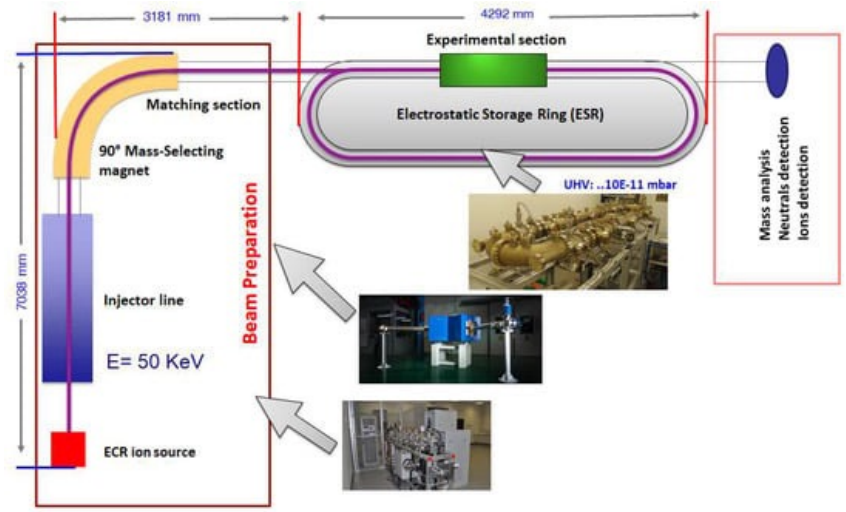
Linear Accelerators



Cyclotrons



Storage Rings



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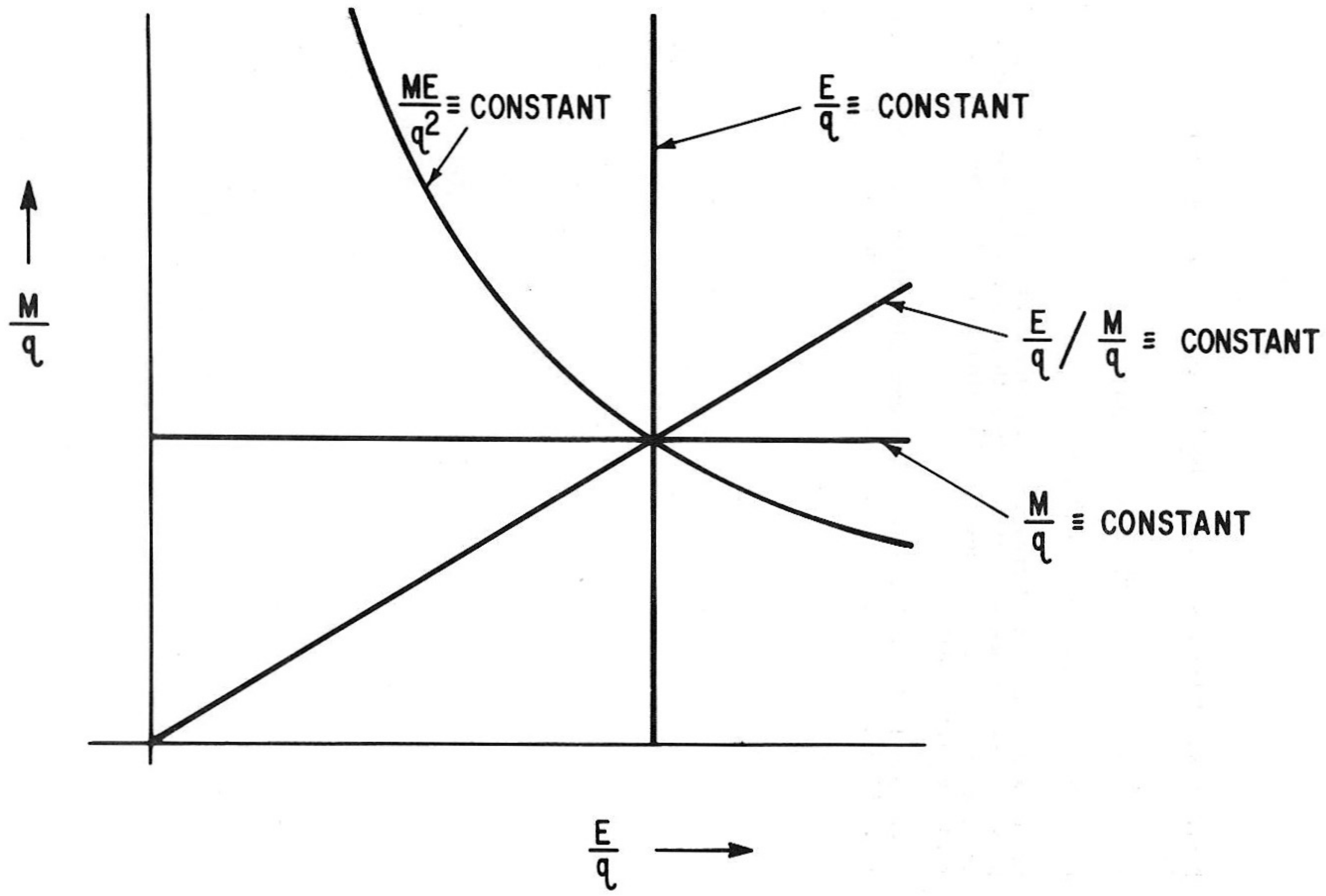
Nuclear Physics Tools – Ion Filters

Magnets

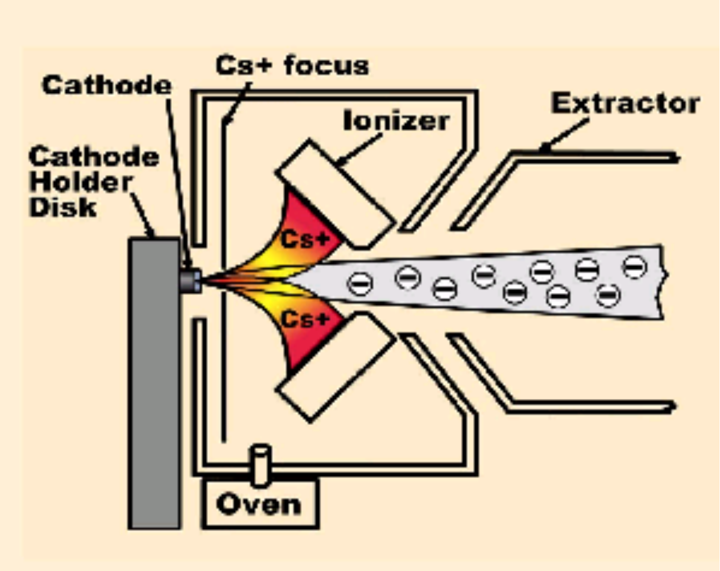
Electrostatic analyzers

Velocity Filters

Cyclotron frequency

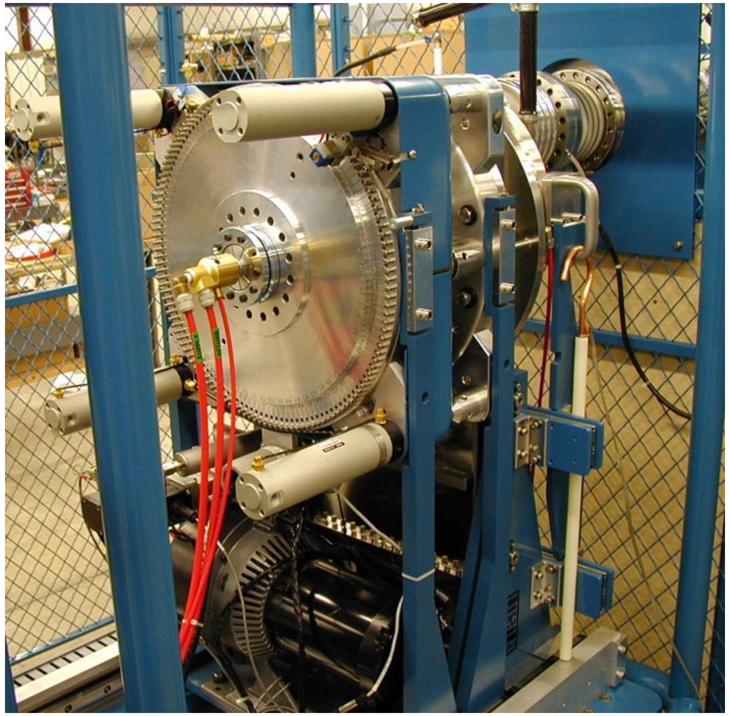


NP Tools - Ion Sources

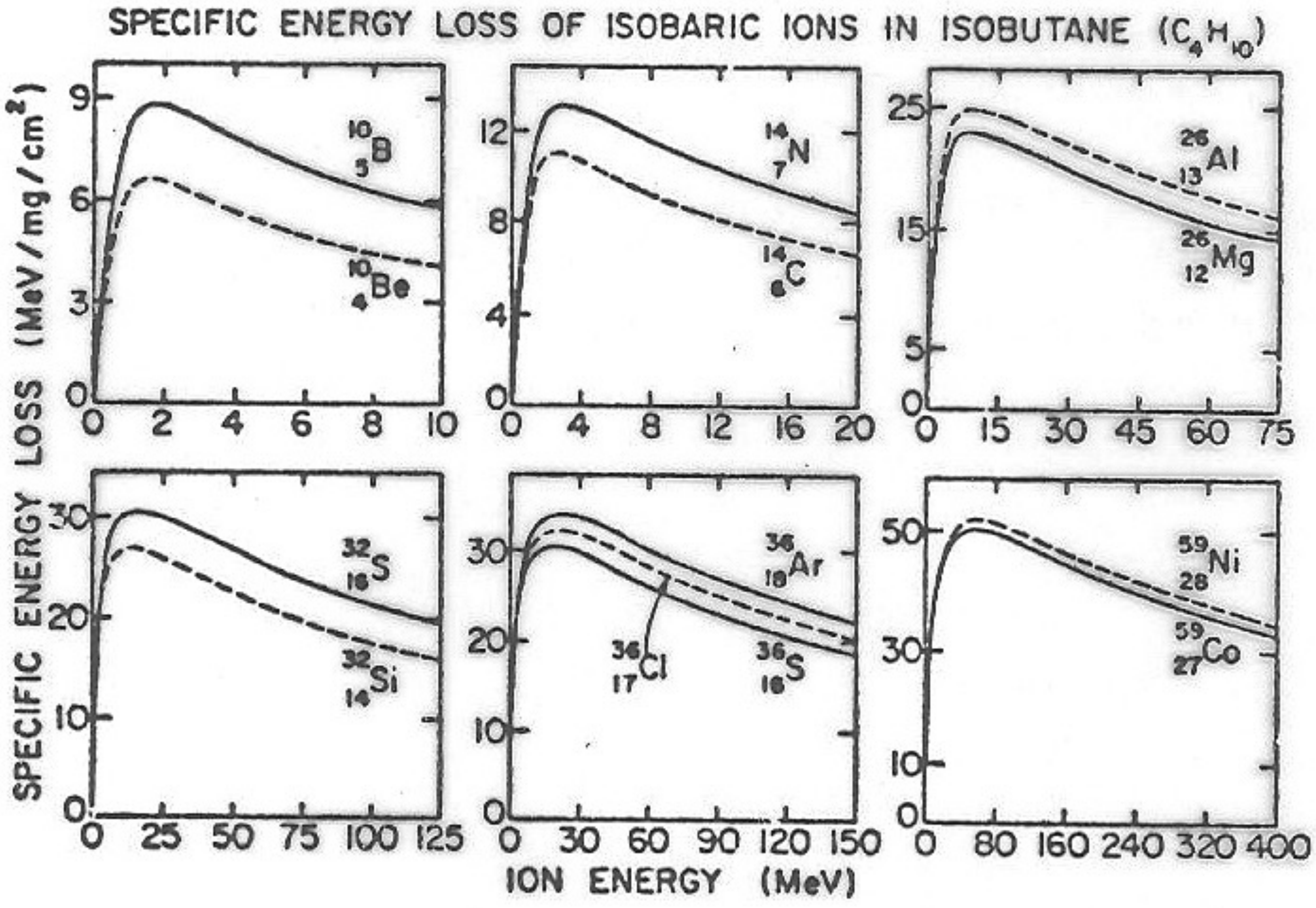


A typical sputter source heated Cs reservoir, an ionizer producing a focused Cs^{+} beam at the sample, and an extraction electrode to accelerate and focus secondary negative ions from the sample into the injection beamline.

Important issues for AMS:
Memory effects
Multiple samples
High currents



NP Tools- Specific Energy Loss for pairs of isobars

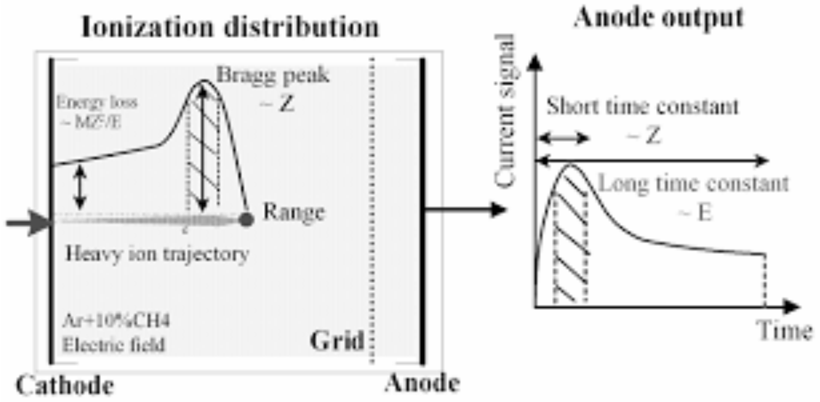


MeV energies

Interaction with detector

Example: Isobutane

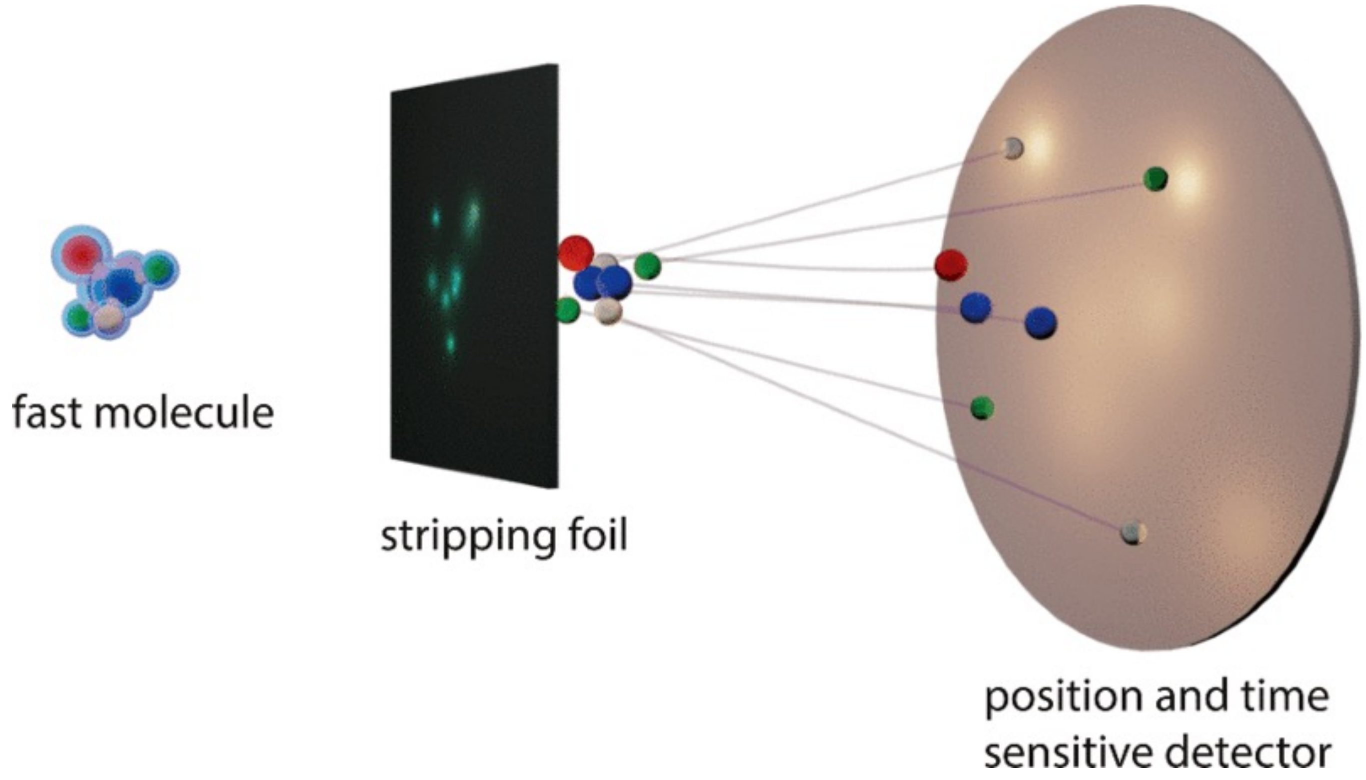
Use of Bragg detectors digitize the "track"



NP tools - Foil induced Coulomb explosion of molecules

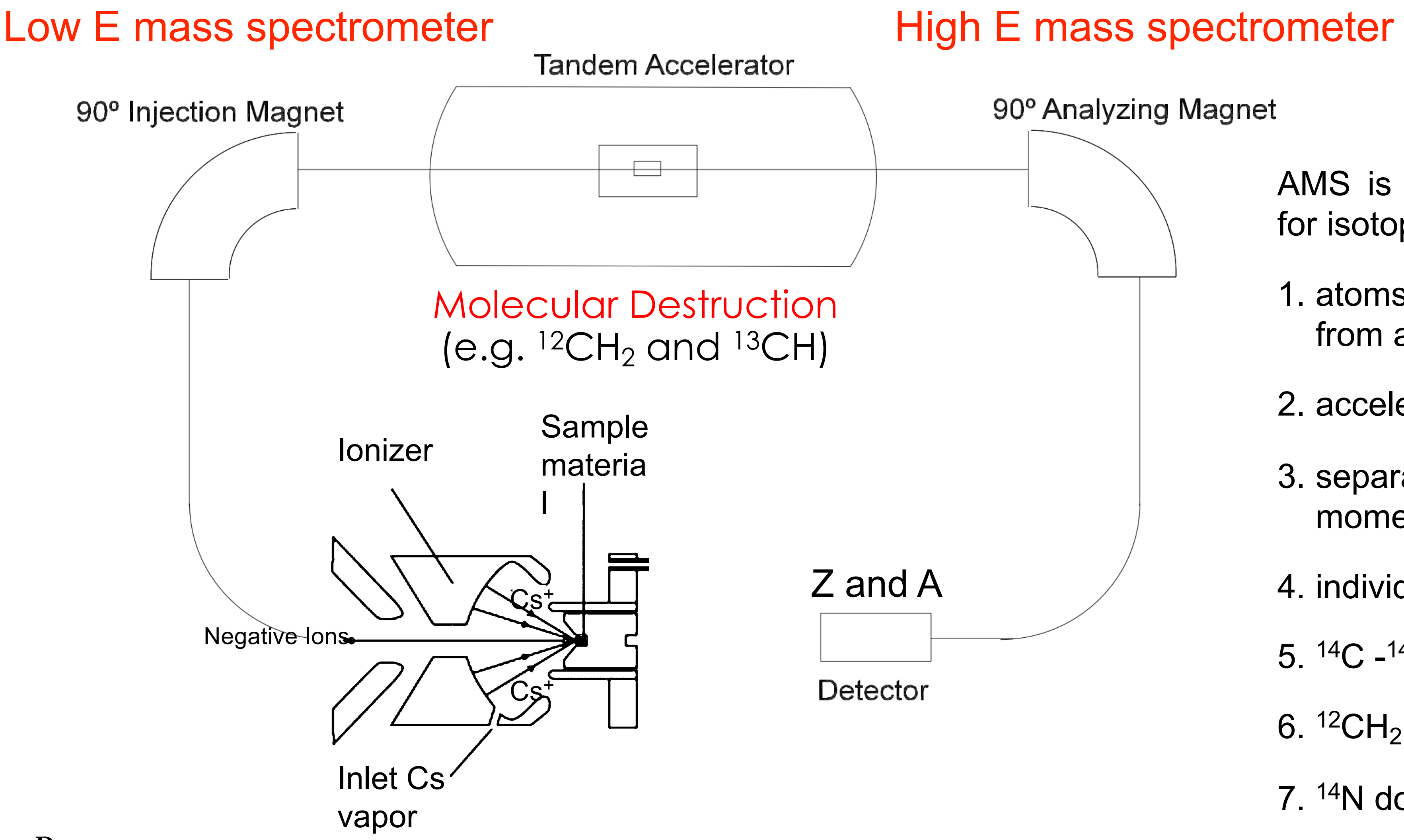
Direct imaging of the molecular structure

Technique pioneered by Argonne, Lyon and Rehovot groups using small accelerators



PHYSICAL REVIEW A 90, 052503 (2014)

Accelerator Mass Spectrometry



AMS is the most sensitive technique for isotopic analysis:

1. atoms and molecules extracted from a sample are ionized
2. accelerated to high energies
3. separated according to their momentum, charge and energy
4. individually counted.
5. ^{14}C - ^{14}N mass difference 1 in 10^5
6. $^{12}CH_2$ - ^{14}C mass difference 1 in 10^3
7. ^{14}N does not form negative ions

NP tools - People - AMS pioneers

Study of $^{12}CH_2^{2+}$ and other doubly charged molecules

THE $^{12}CH_2^{2+}$ MOLECULE AND RADIOCARBON DATING BY ACCELERATOR MASS SPECTROMETRY

NIM B5 (1984) 208

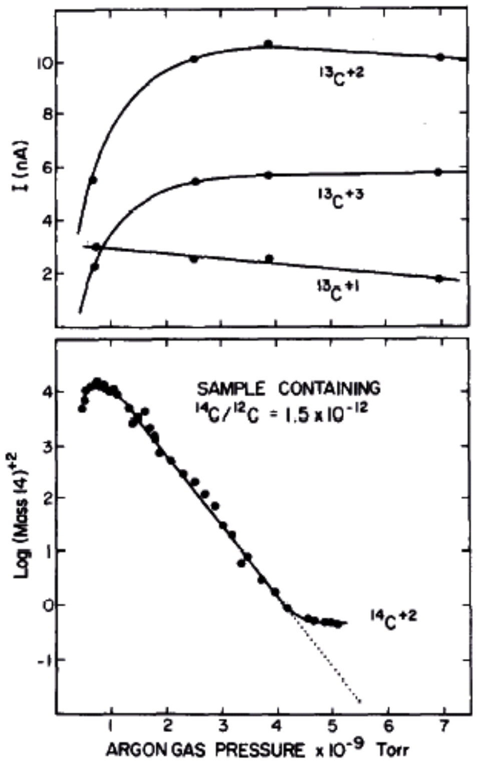
H.W. LEE, A. GALINDO-URIBARRI *, K.H. CHANG, L.R. KILIUS and A.E. LITHERLAND

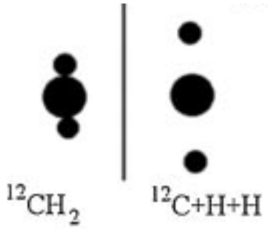
ISOTRACE Laboratory, University of Toronto, Toronto, Ontario M5S 1A7, Canada

The $^{12}CH_2^{2+}$ molecule has been studied and it was found that the molecule can be effectively eliminated thus allowing detection of $^{14}C^{2+}$ at low terminal voltages of a tandem accelerator. Some implications of this discovery for radiocarbon dating are discussed.

This discovery led to the design and construction of smaller dedicated AMS machines

Atomic





$^{14}C^{+2}$

Exponential destruction of molecules in the gas stripper at the HV terminal

Oak Ridge National Laboratory

Volume 83, Issue 7
1 October 1985

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Article Contents

REFERENCES

RESEARCH ARTICLE | OCTOBER 01 1985

Beams of doubly ionized molecules from a tandem accelerator

A. Galindo-Uribarri; H. W. Lee; K. H. Chang

Check for updates

J. Chem. Phys. 83, 3685–3693 (1985)
https://doi.org/10.1063/1.449123   **Article history**

We report the observation of 3–4 MeV beams of several species of small doubly charged molecules ($^{10}B^{11}B^{++}$, $^{10}B^{++}{}_2$, $^{11}B^{12}C^{++}$, $^{9}Be^{14}N^{++}$, $^{12}C^{13}C^{++}$, $^{12}C^{13}CH^{++}$, $^{12}C^{14}N^{++}$, $^{12}C_2H^{++}$, $^{12}CH^{++}{}_2$, $^{9}Be^{16}O^{++}$, $^{10}B^{16}O^{++}$) emerging from a tandem accelerator. These observations significantly increase the number of such molecules known. All are probably produced in metastable states with lifetimes longer than 1 μs. Substantial fluxes (>10^8 molecules per second was shown for CN^{++}) of these doubly charge[d] molecules were obtained and they were identified by observing the fragmentation of molecular ions after passing throu[gh a] carbon foil. In some cases the molecules are observed to decay in flight. An efficiency of 10^{-4} in producing mass 25 mo[lecules] ($^{12}C^{13}C^{++}$ +$^{12}C_2H^{++}$) has been measured. Advantage is taken of the existence of "atomic interference free" mass regions, where no atomic negative ions are formed, therefore allowing the production of pure molecular beams. Some implications of this work for accelerator mass spectrometry (AMS) are discussed. An application of doubly positive charged molecules in a search for doubly negative charged molecules was made, establishing an upper limit of 1:10^{10} of $^{10}B^{11}B^{-}$/$^{10}B^{11}B^{-}$ and of 1:10^9 of $^{12}C^{13}C^{-}$/$^{12}C^{13}C^{-}$.

PDF
Help

Only about 3 cases reported Molecular Spectra …G. Herzberg

- *Vibrationally hot (T ~ 5000 ^{O}K) XY^- molecules produced in the sputtering process on solids charge change to XY^{++} after MeV collisions with argon gas.*
- *Intensities > 10^8 CN^{++} per second*
- *"Atomic interference free" mass regions where no atomic negative ions are formed*

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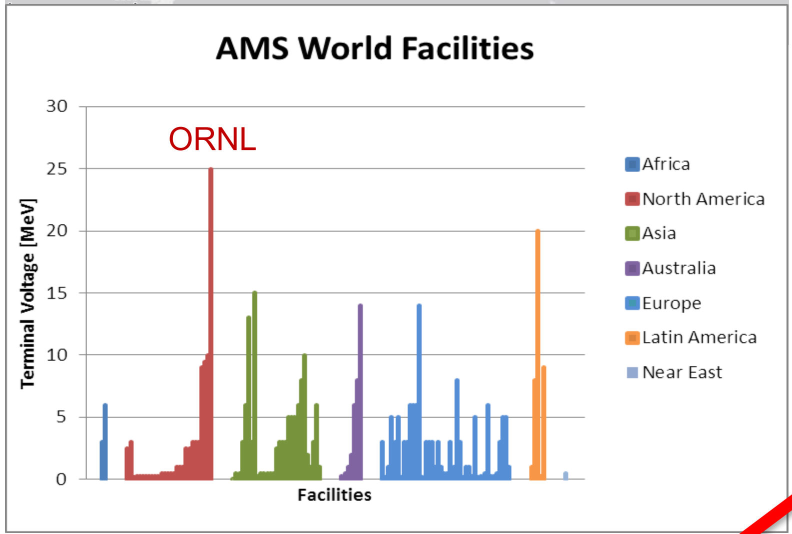
NP Tools - AMS



$^{14}C^{+1}$

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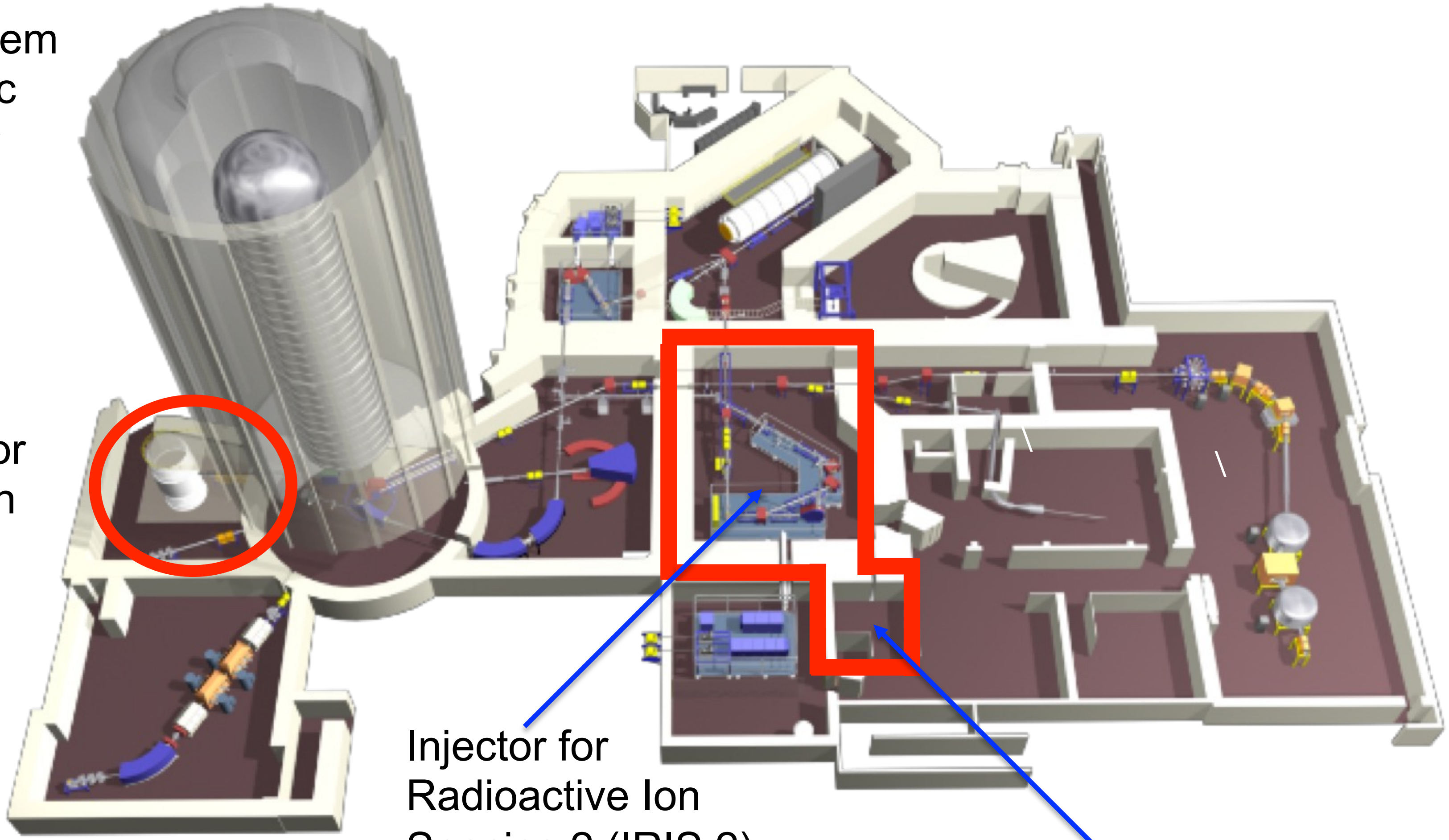
Holifield Radioactive Ion Beam Facility (HRIBF): AMS and RIMS at ORNL



HRIBF shut down in 2012

AMS and Radioactive Ion Beams (RIB)

Most interesting RIBs are short-lived
^{17}F ($t_{1/2}$ = 65 s)

- Common problems/needs:
  - Production
  - Isobar removal
  - Stable machine operation
  - Low intensity beam diagnostics

In AMS: long-lived species
^{36}Cl ($t_{1/2}$ = 3.01 x 10^{6} a)

- Good detection tools
  - Bragg Detector
  - Projectile X-ray
  - TOF
  - 2D channel Plates
  - Gas filled magnet
  - Beam monitors

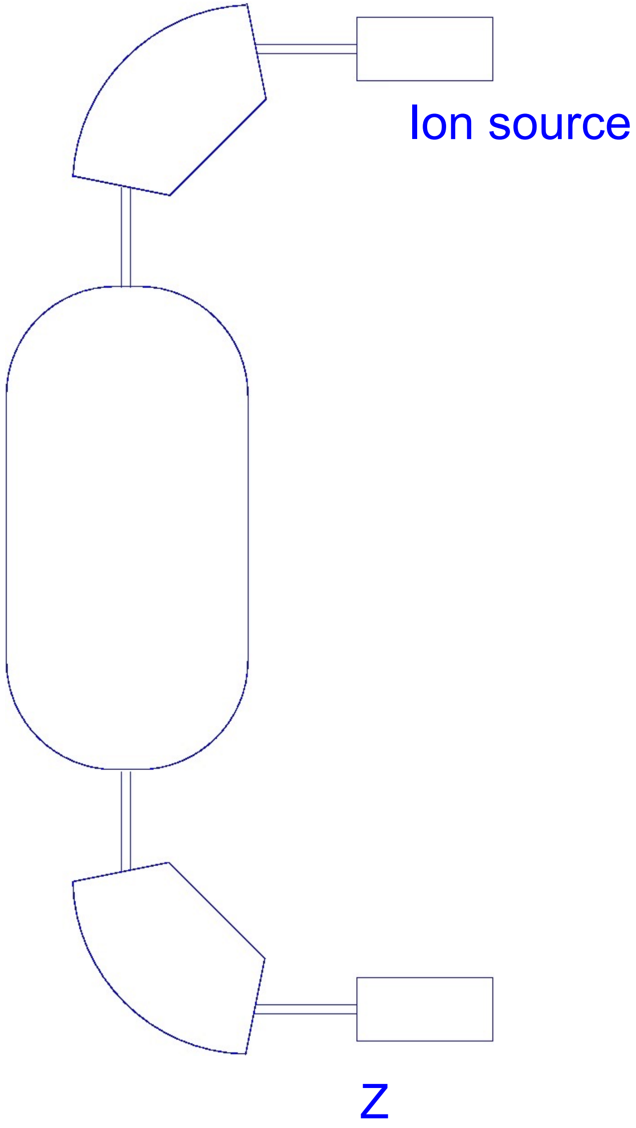
We have concentrated in:

Development of AMS methods. Pilot experiments. Proof-of-principle tests

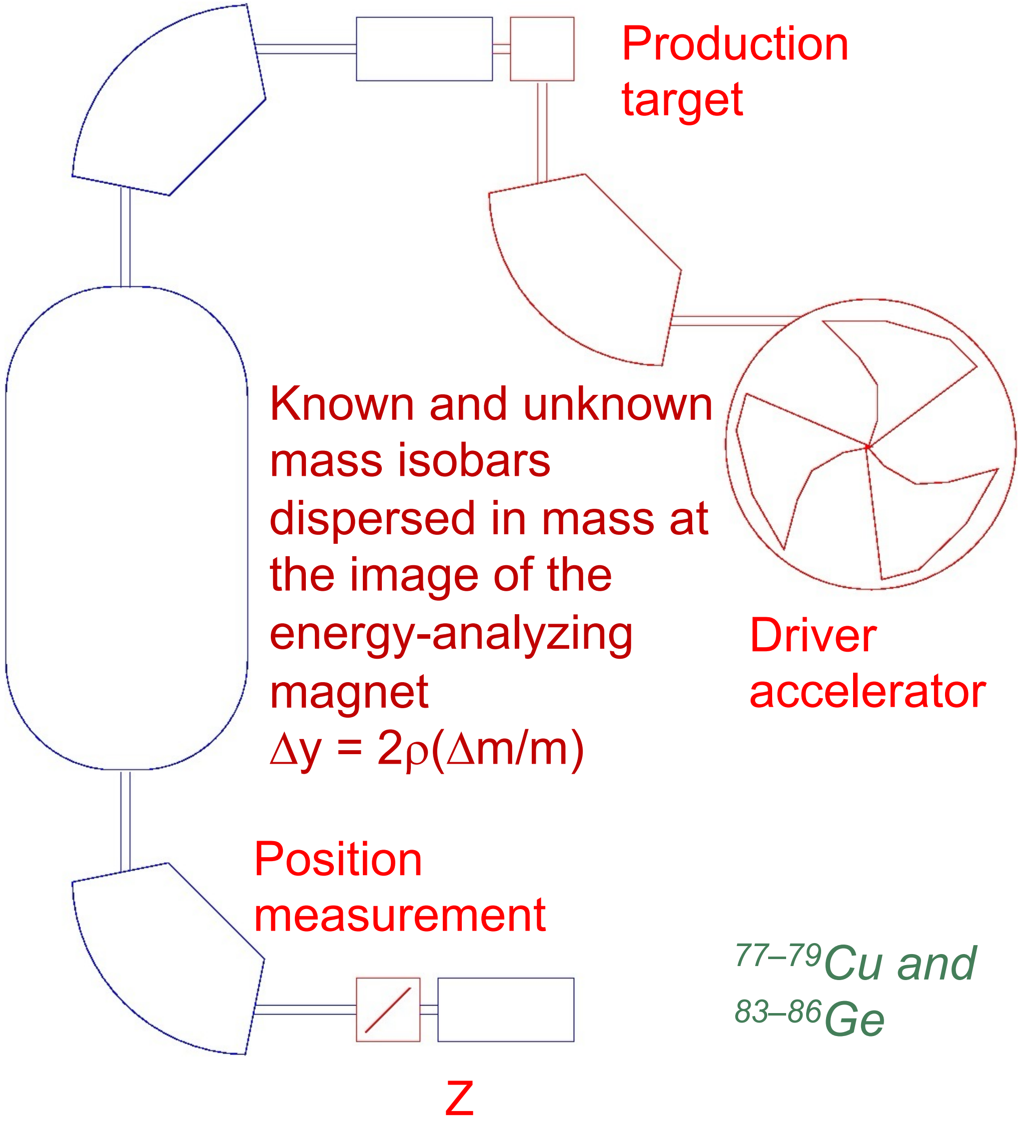
Methodology Transmission Ion Optics Detection Systems

NP Tools – AMS and Radioactive Ion Beams

abundance (AMS)



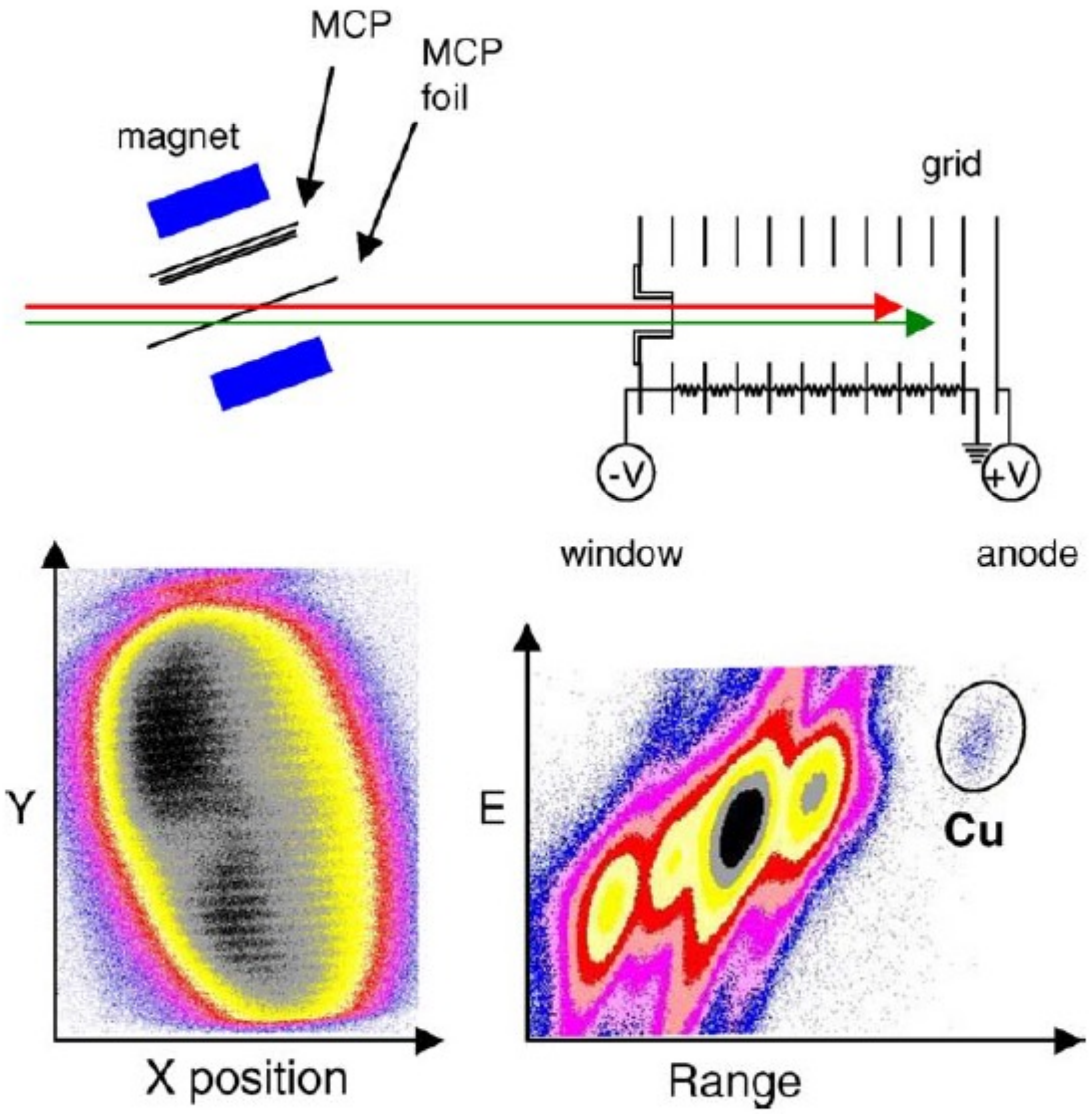
masses (RIB)



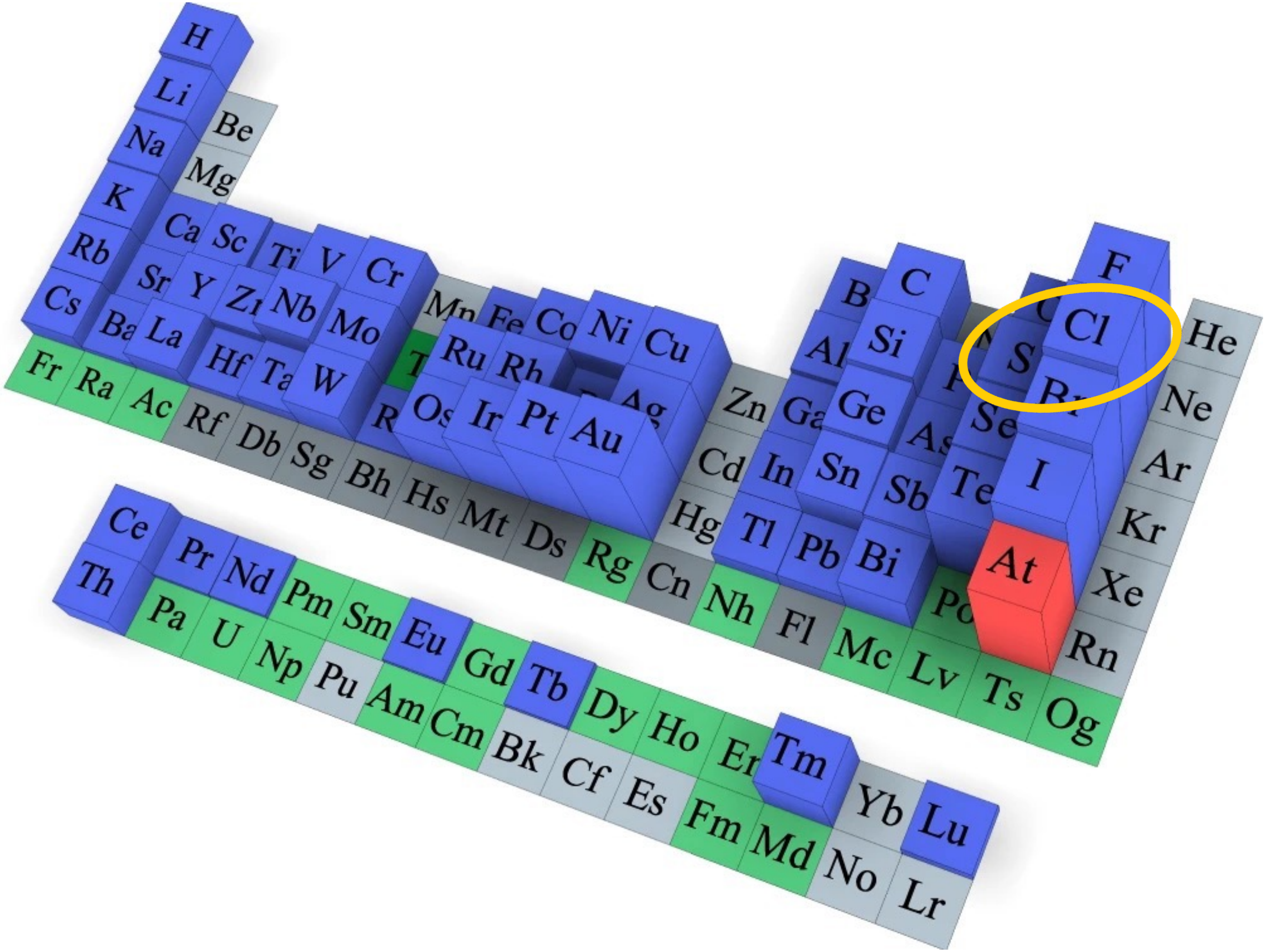
$^{77–79}$Cu and $^{83–86}$Ge

P. A. Hausladen et al., NIM B 223 (2004) 176 and IJMS 251, 2-3 (2006) 119

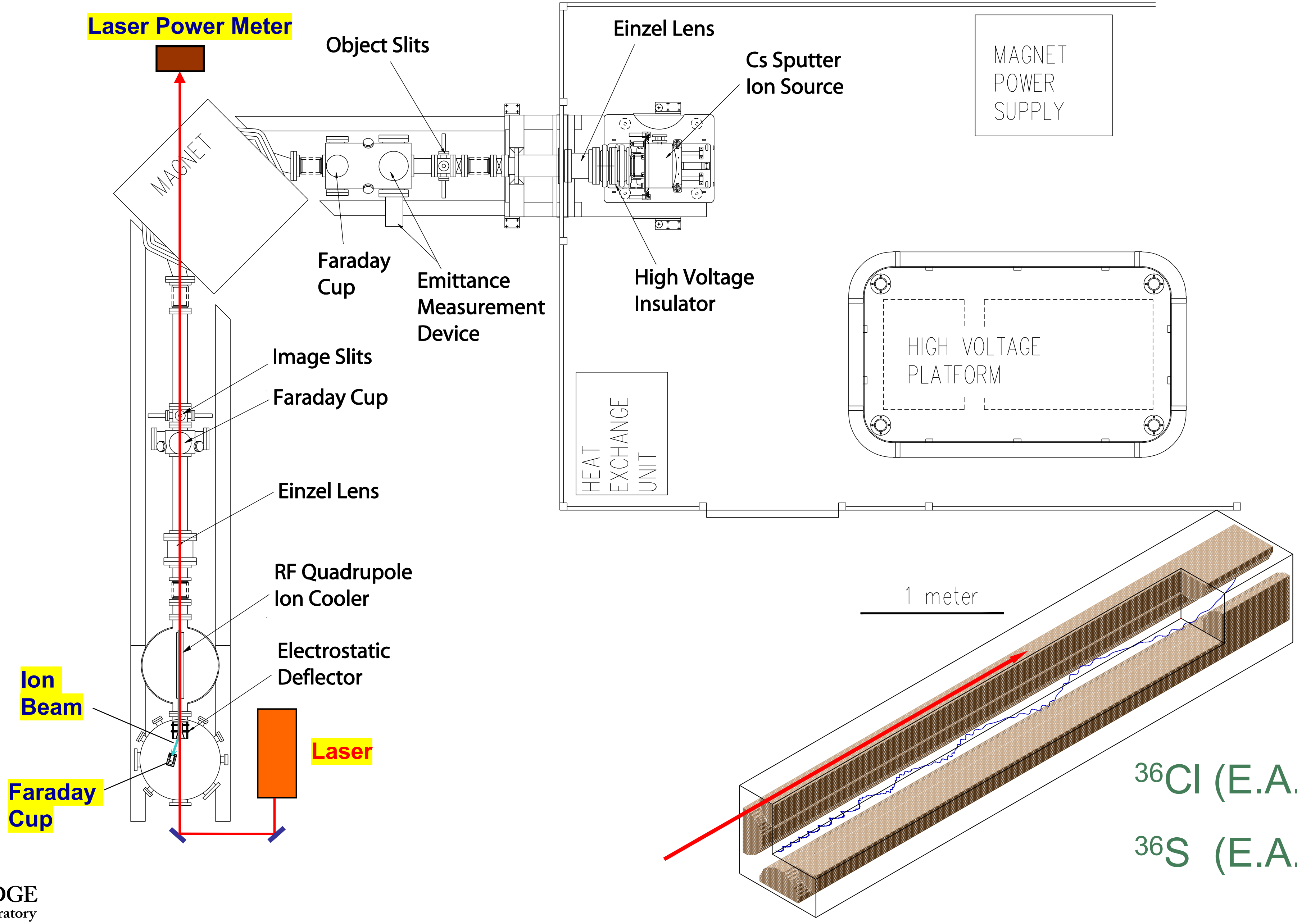
AMS Mass Measurements



Electron affinities across the periodic table.



Experimental Setup - Photodetachment

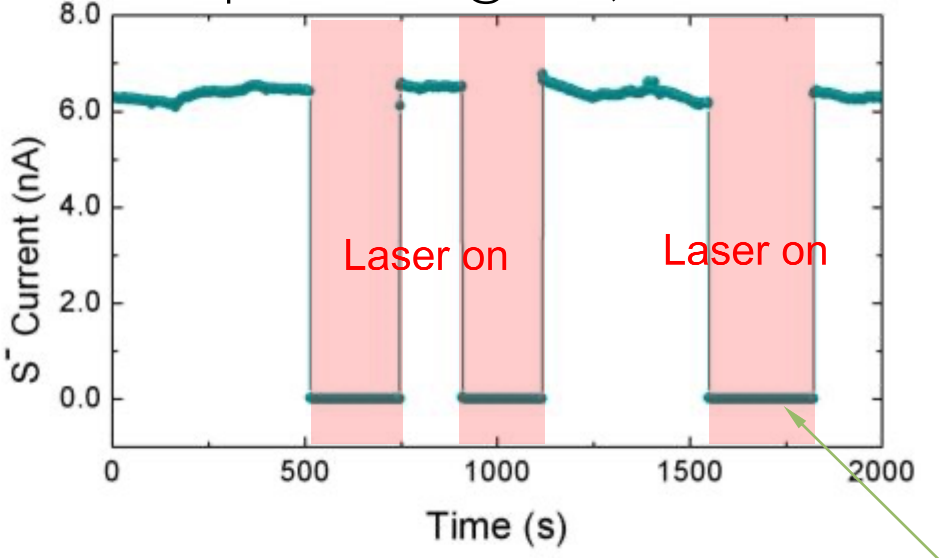


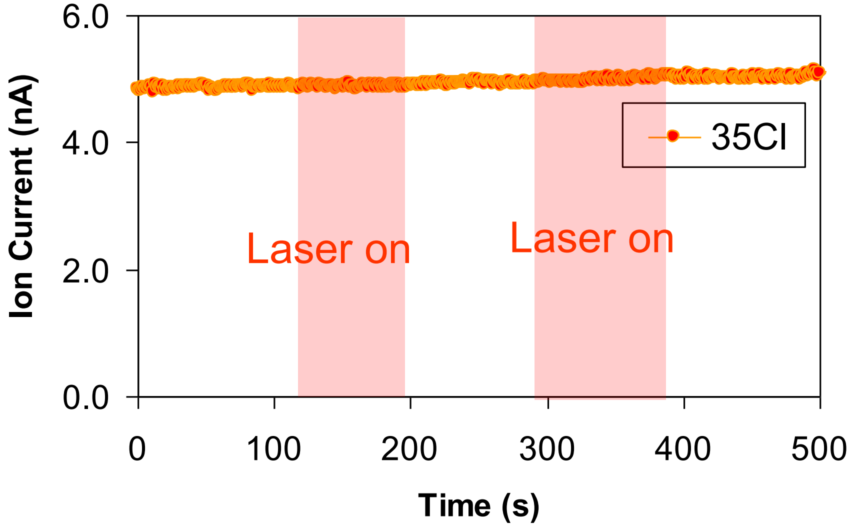
^{36}Cl (E.A. = 3.62 eV)

^{36}S (E.A. = 2.08 eV)

Photodetachment

Laser power ~2.5 W @ 3 kHz, He ~ 100 mTorr





Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms

Volume 268, Issues 7–8, April 2010, Pages 834-838

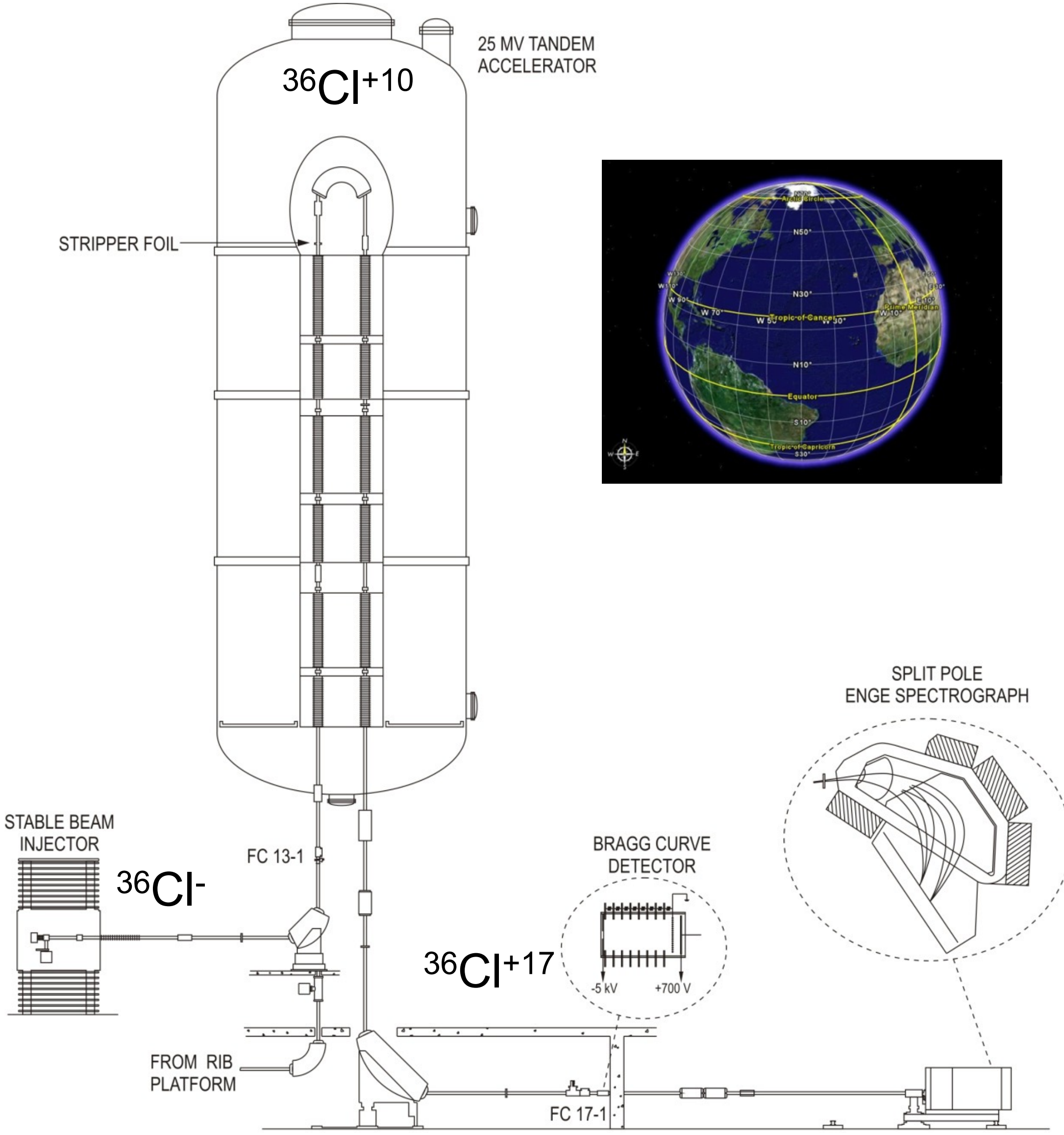
Selective isobar suppression for accelerator mass spectrometry and radioactive ion-beam science

A. Galindo-Uribarri [a, b], C.C. Havener [a], T.L. Lewis [b], Y. Liu [a]

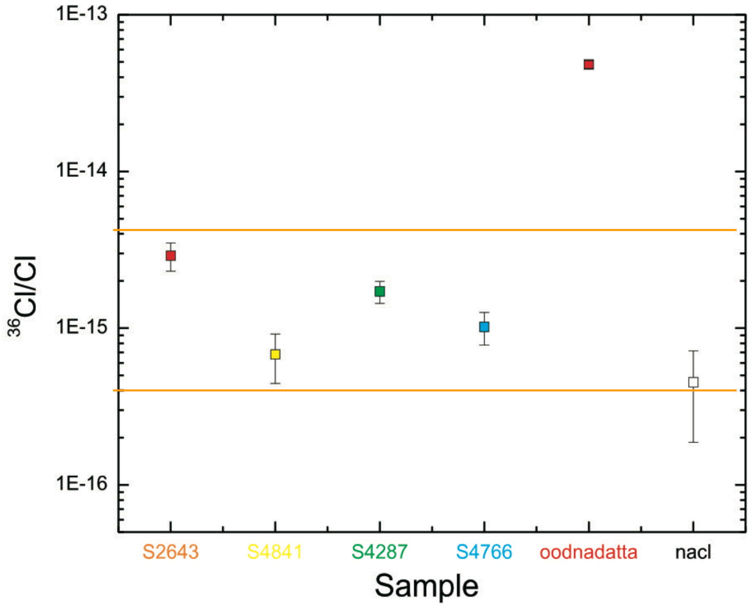
detection limit: 2 pA

- **No significant reduction of Cl observed.**
- **S suppression is about 1% when cooler is not used.**

AMS measurement $^{36}Cl^{-}$ Pushing the limits of AMS by an order of magnitude



^{36}Cl in seawater samples from around the world: comparison



Measurement of ^{36}Cl in seawater samples

A. G-U, et al. NIM B 259 (2007)123

Sputtered molecular fluoride ions XF_n^-

Super-halogens.

Have electron affinities much higher than those of the halogens themselves and so are of great interest to AMS

Their great electron binding energies make it possible to produce large currents with Cs^+ sputter sources

A systematic study of anions of the type XFn (n being the number of F atoms) was therefore undertaken monitoring the secondary-ion flux in a mass spectrometer.

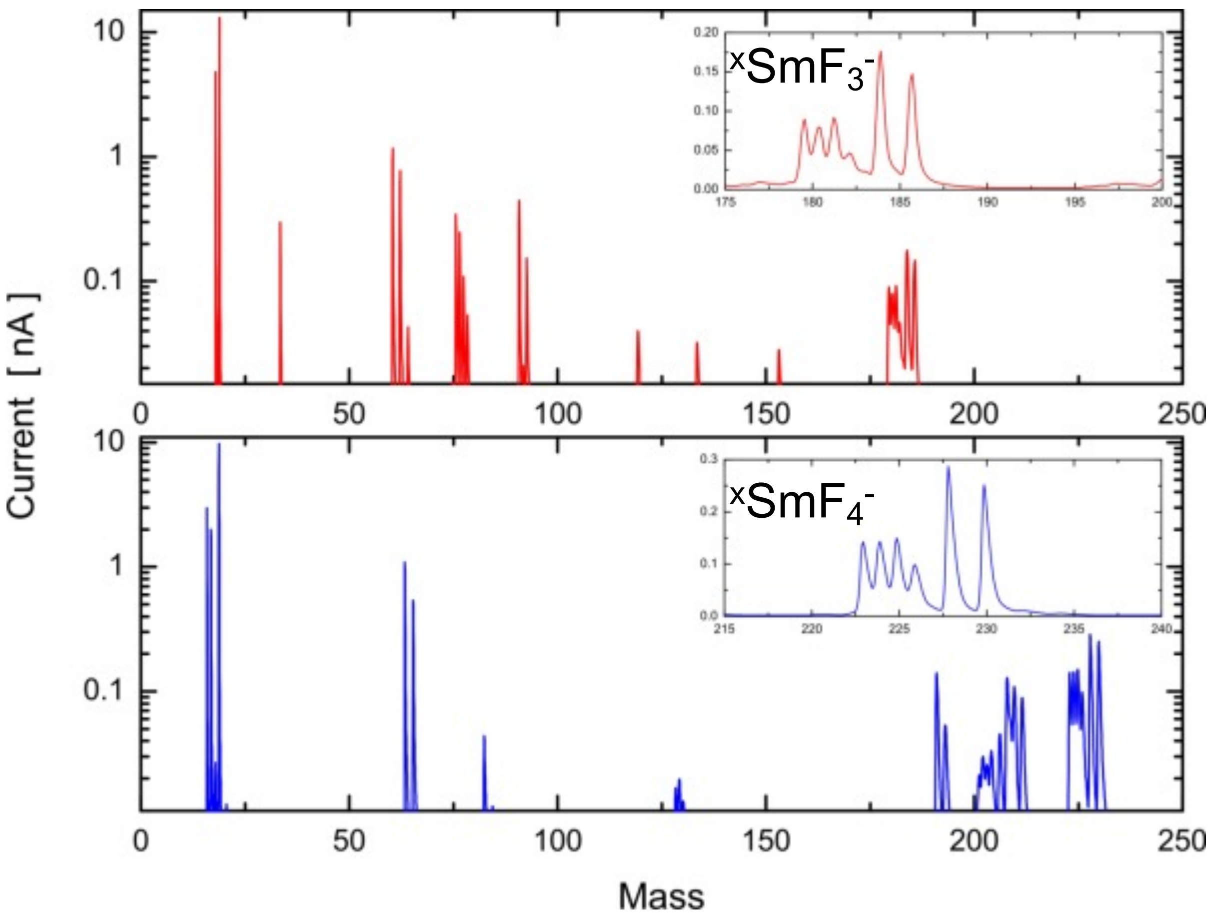
$^{x}SmFn^{-}$ mass scans

The sputtered flux is composed of atoms as well as molecules,

the production of an abundant flux of anions by sputtering the target with Cs+ ions is a prerequisite for the ultrahigh sensitivity of AMS

Some molecular ions were found to be emitted in sputtering with (much) higher intensity

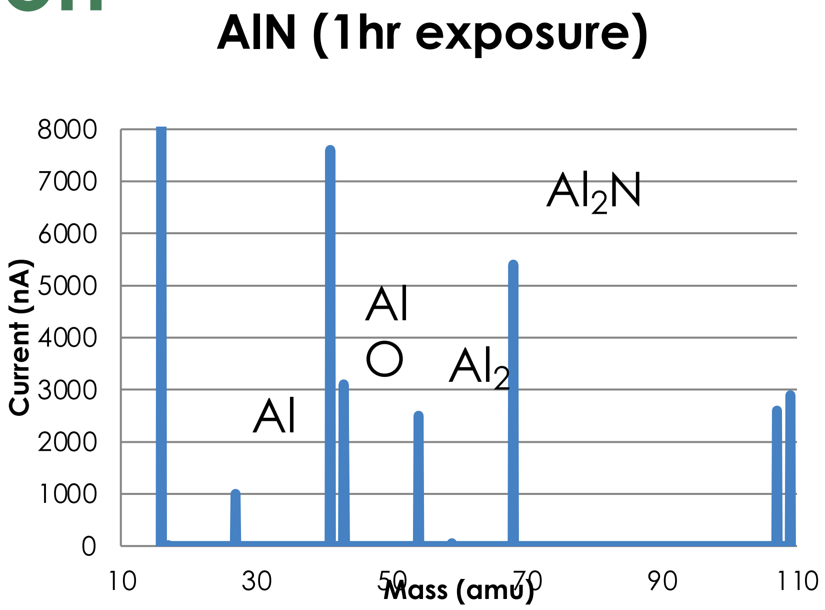
Their possible formation and ionization processes and relative abundances are still not known in detail.



The correctness of the isotopic patterns was checked

Use of Molecules (AlN) for ^{26}Al detection

- Develop a new and improved technique for the ultrasensitive AMS measurements of ^{26}Al for geological samples
- Demonstrating other source materials can outperform Al_2O_3

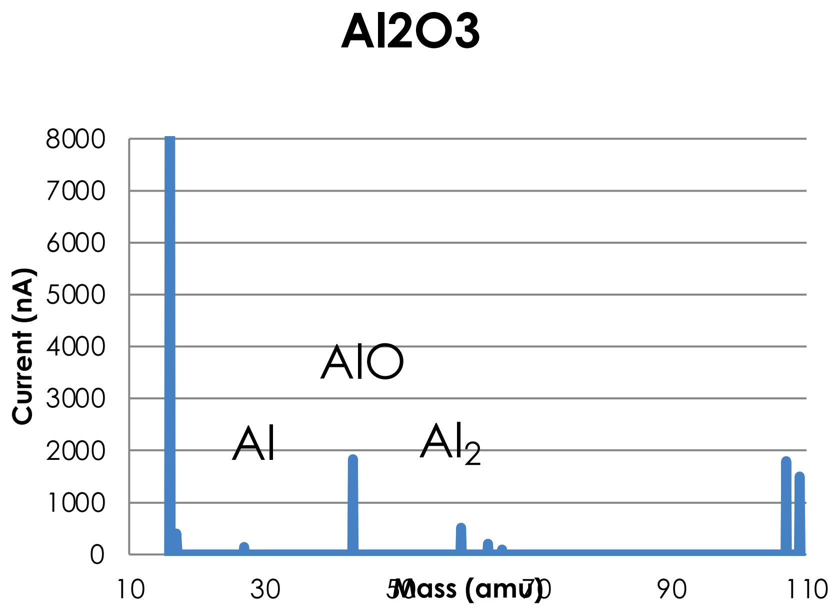


Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms

Volume 361, 15 October 2015, Pages 281-287

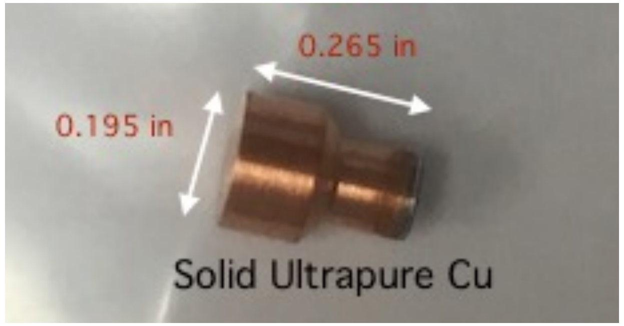
The use of aluminum nitride to improve Aluminum-26 Accelerator Mass Spectrometry measurements and production of Radioactive Ion Beams

Meghan S. Janzen [a b c], Alfredo Galindo-Uribarri [a b c], Yuan Liu [a], Gerald D. Mills [a], Elisa Romero-Romero [a c], Daniel W. Stracener [a]

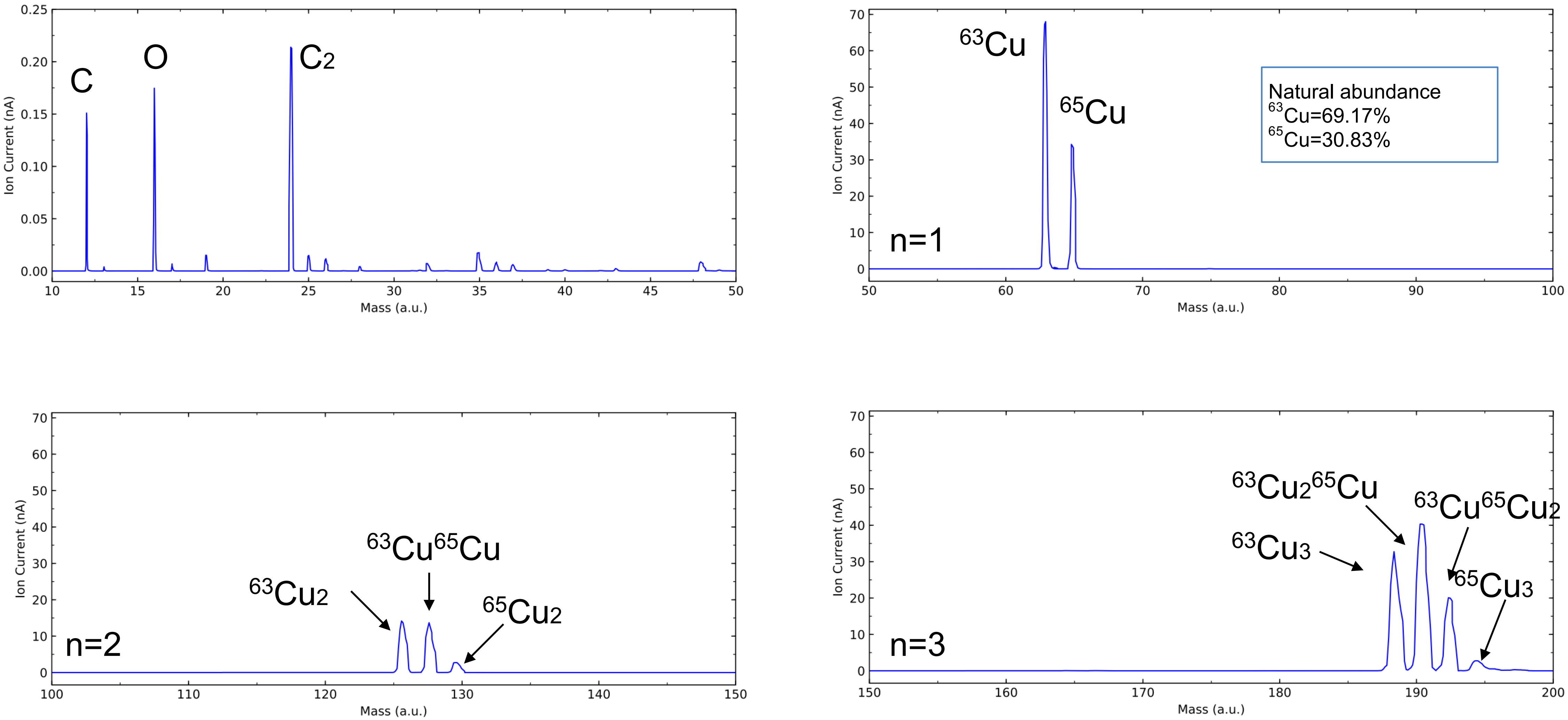


Clusters

- How big?
- Can we form cluster beams of negative ions?
- How intense?
- At what energy?
- How fragile?
- Can we form clusters of same isotope?
- Do the intensities reflect some structure?
- How fast the current drops as a function of n?
- How do the atoms organize?
- Samples of Cu, ultra-pure Cu, ^{63}Cu, ^{65}Cu, Au, C



Ultrapure Cu Mass Scan



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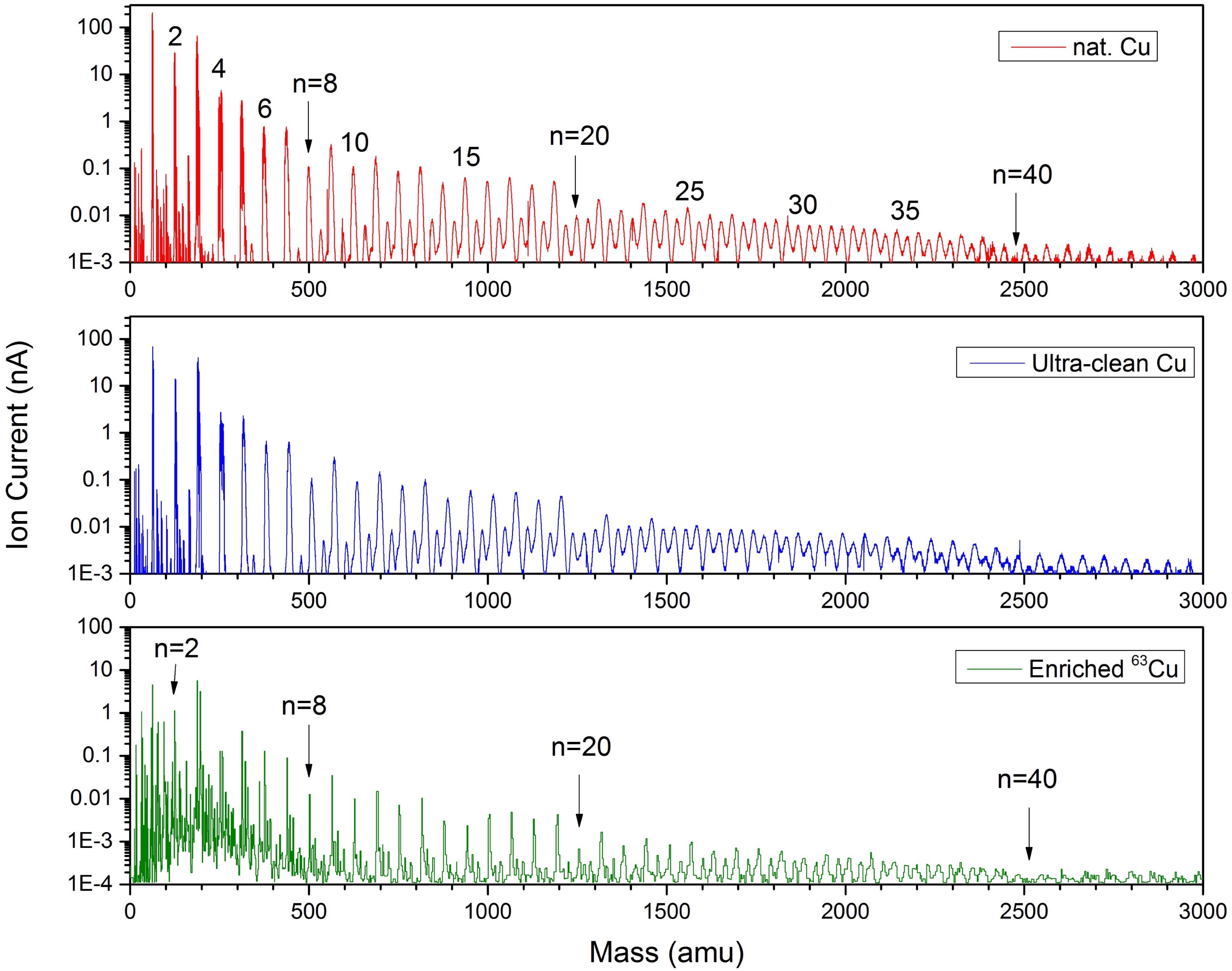
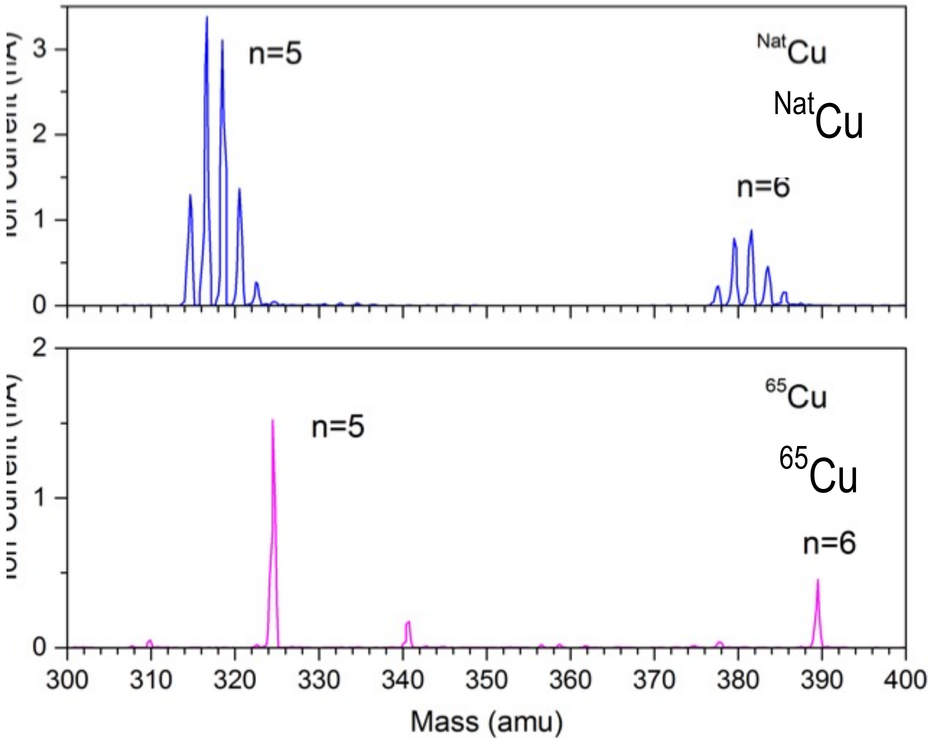
Mass Spectra of Negative Clusters





Magic Numbers n= 2, 8, 20, 40,..

Analogies with Nuclear Physics

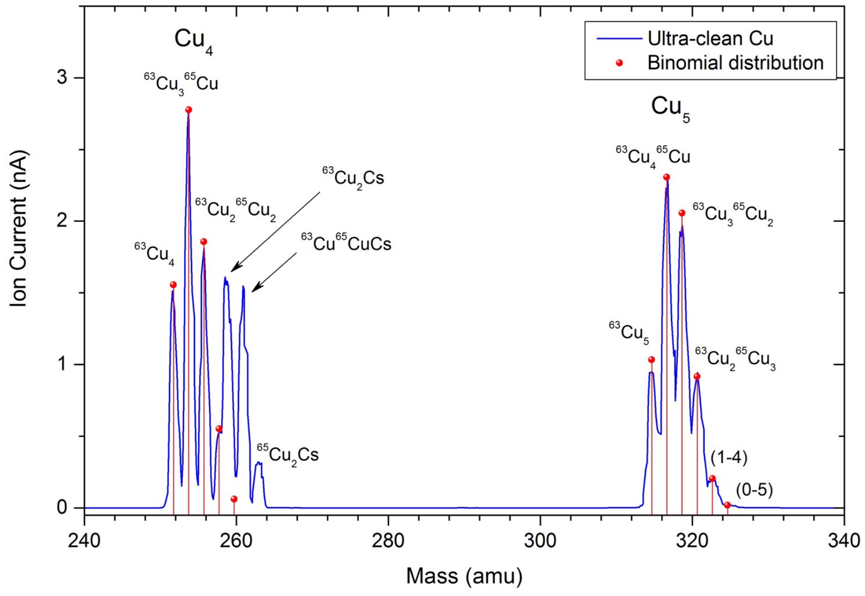
Supershells?

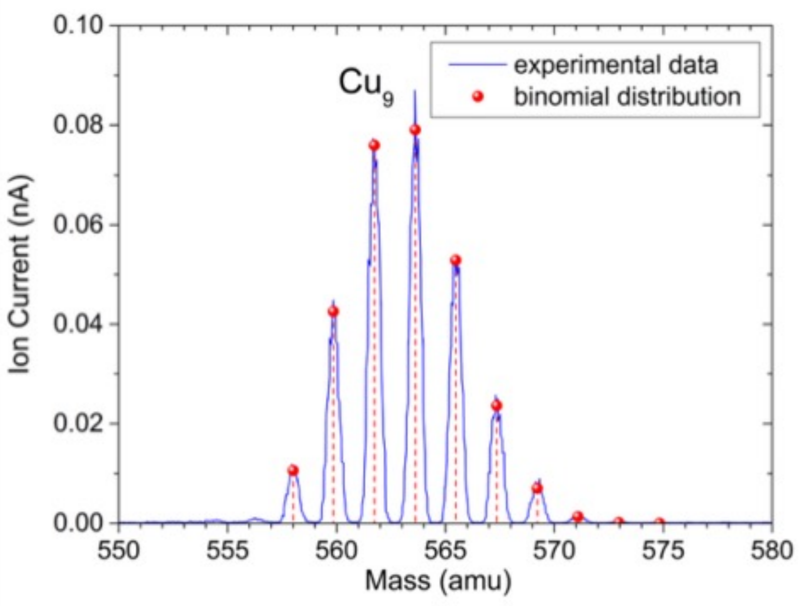
Binomial Distributions

The relative intensities of the $^{63}Cu_x{}^{65}Cu_{n-x}$ compositions follows a binomial distribution

$$F(n,x) = p^x(1-p)^{n-x}\frac{n!}{x!(n-x)!}$$

p= 0.6917, the natural abundance of Cu-63





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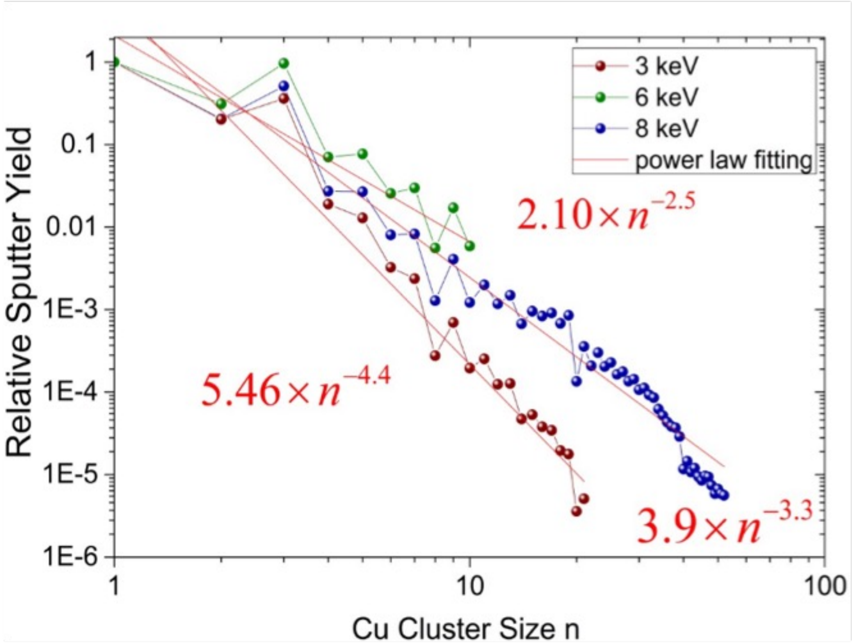
Power Law Dependence

The intensity of sputtered Cu clusters decreases with size n and follows a power law dependence

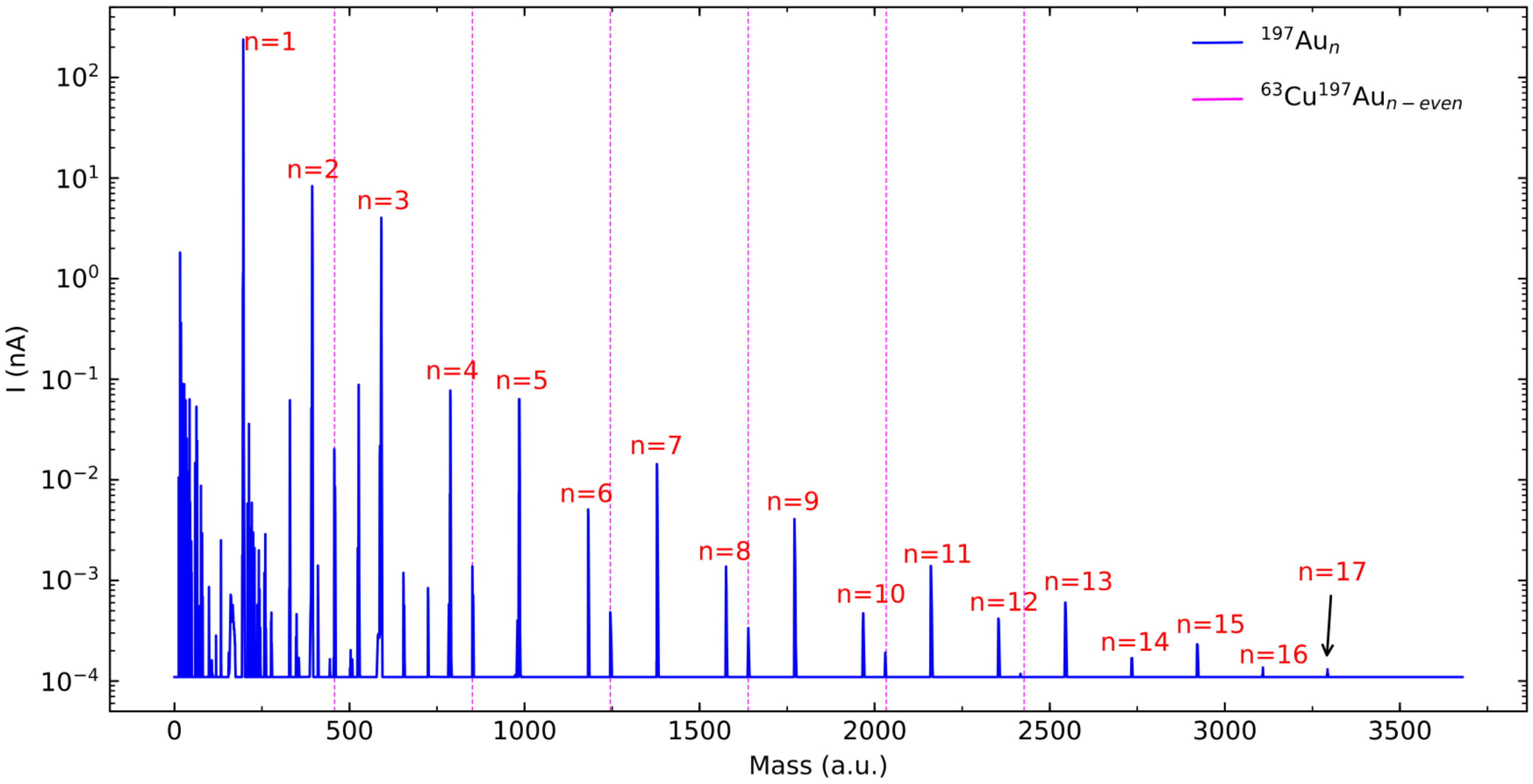
$$Y(n) \propto n^{-\alpha}$$



We learned how to operate the Cs source to optimize the production of clusters relative to atomic ions

Clusters Search

- We continued with clusters in Au and C



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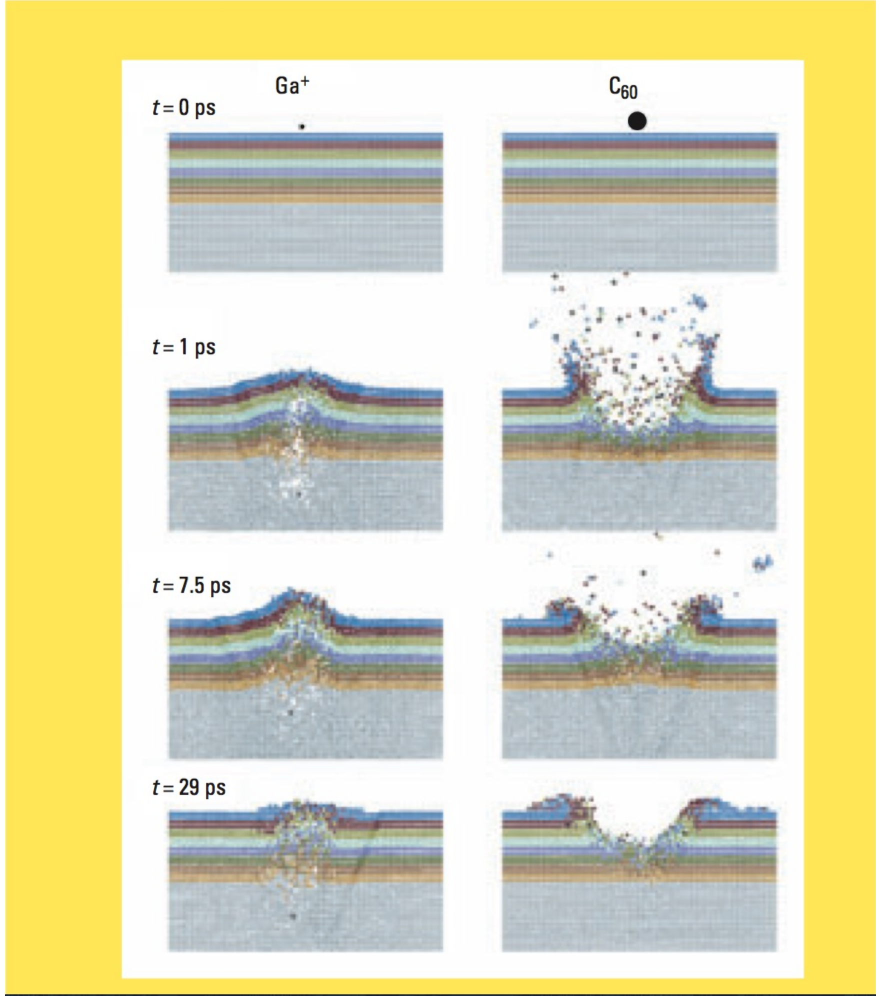
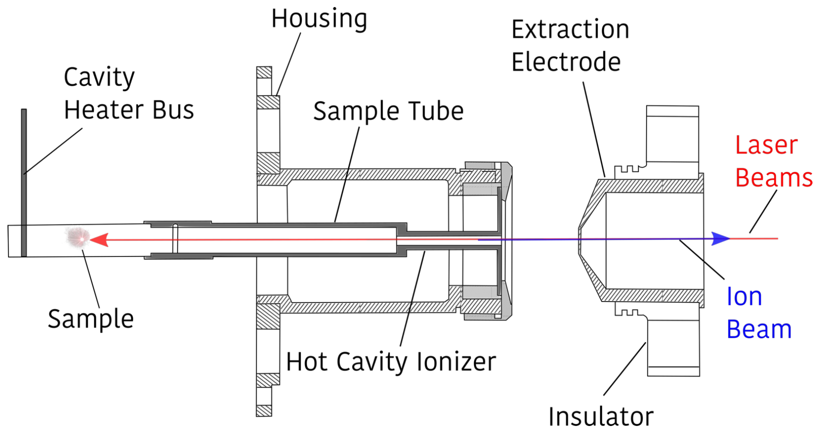
Applications

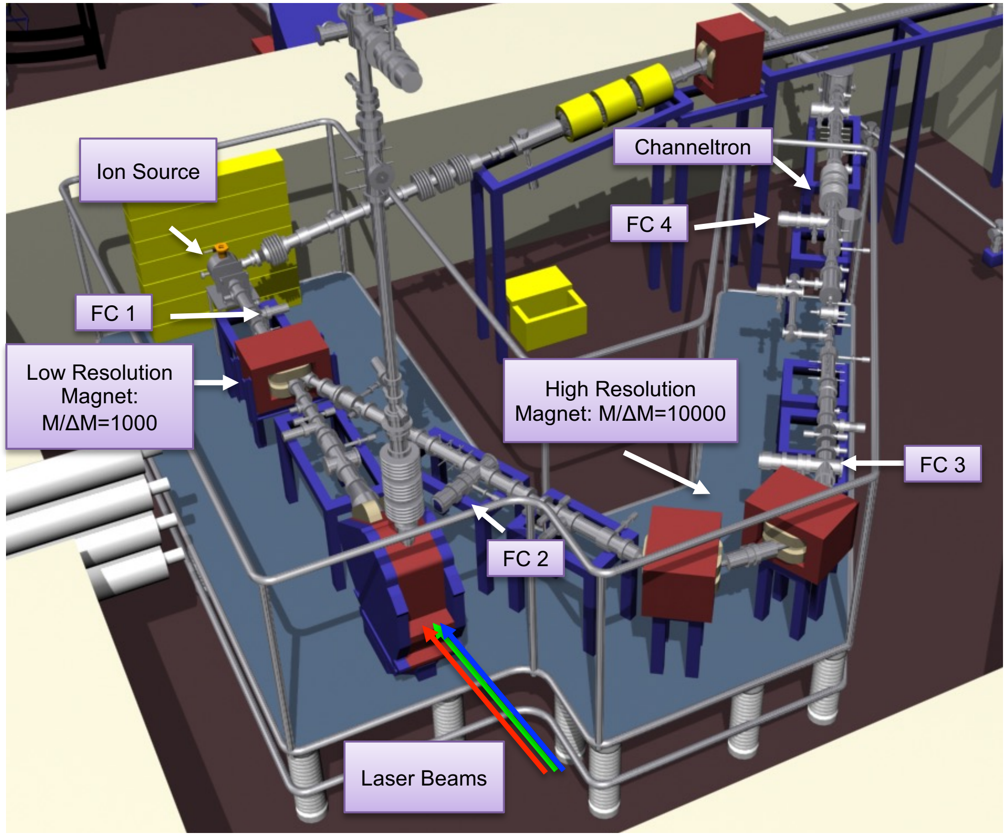
e.g. Biological samples, semiconductors, etc.



Winograd, N. (2005). *Analytical Chemistry*, *77*(7), 142-A.

Injector for Radioactive Ion Species 2 (IRIS 2)



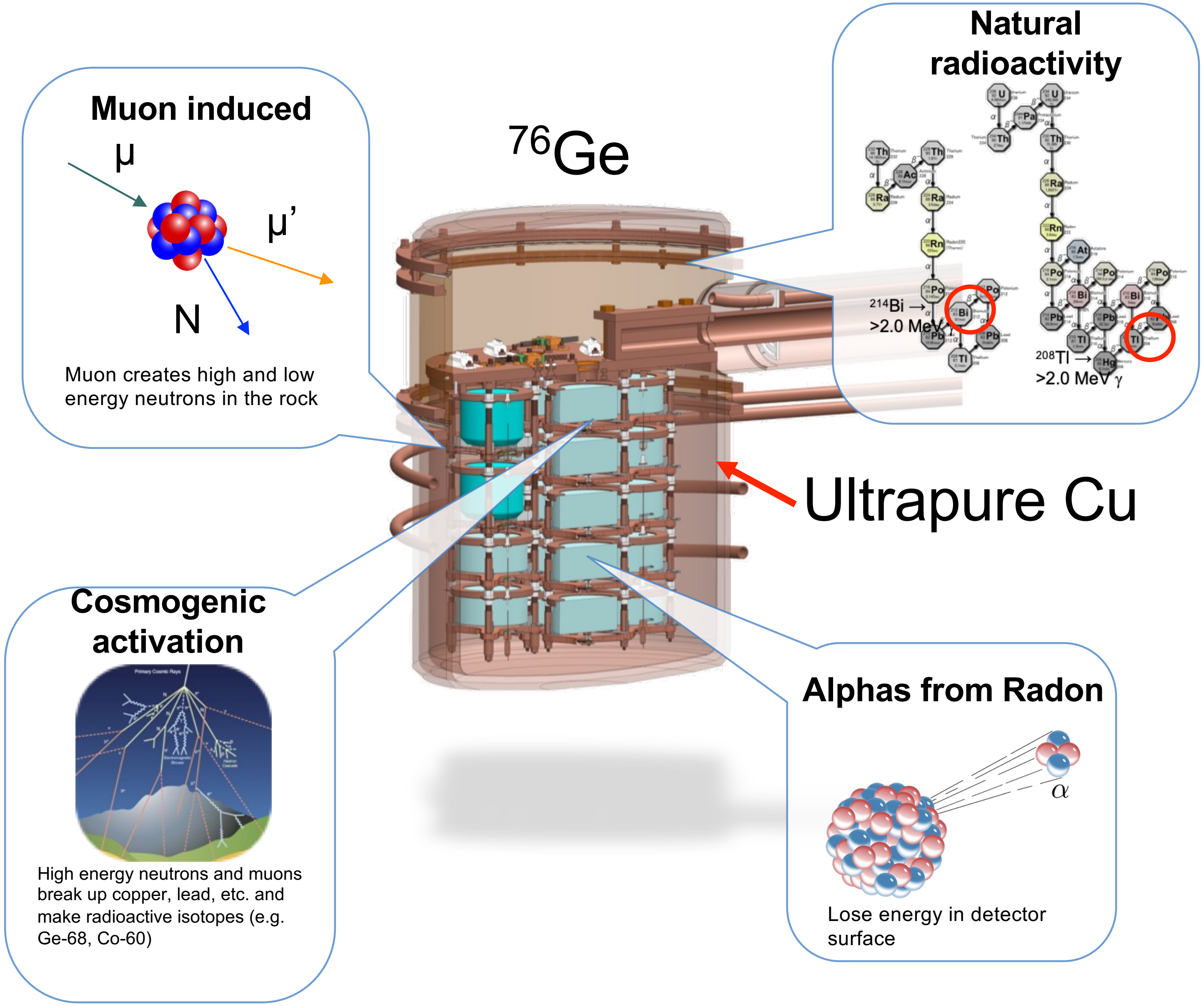


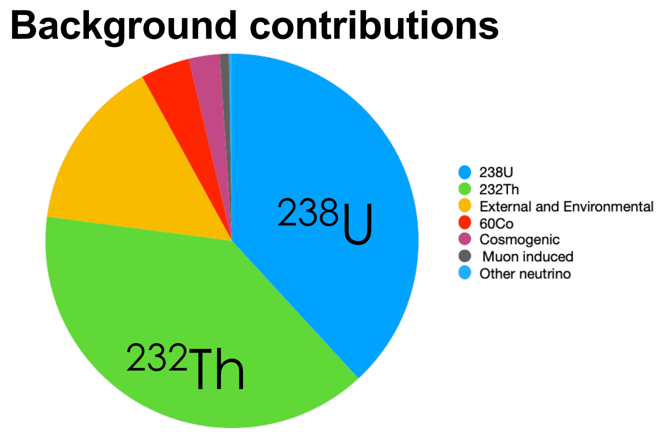
U

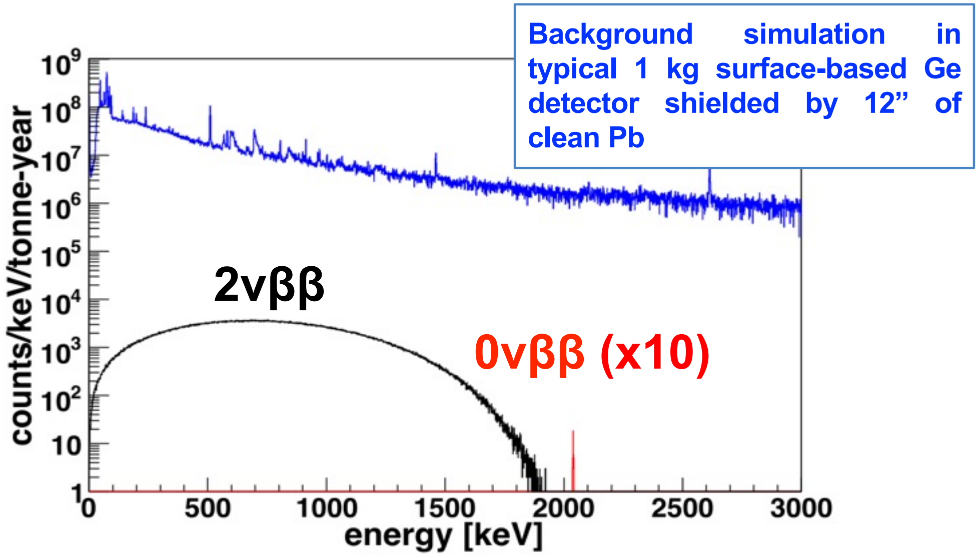
Th

Pu

It's all about background



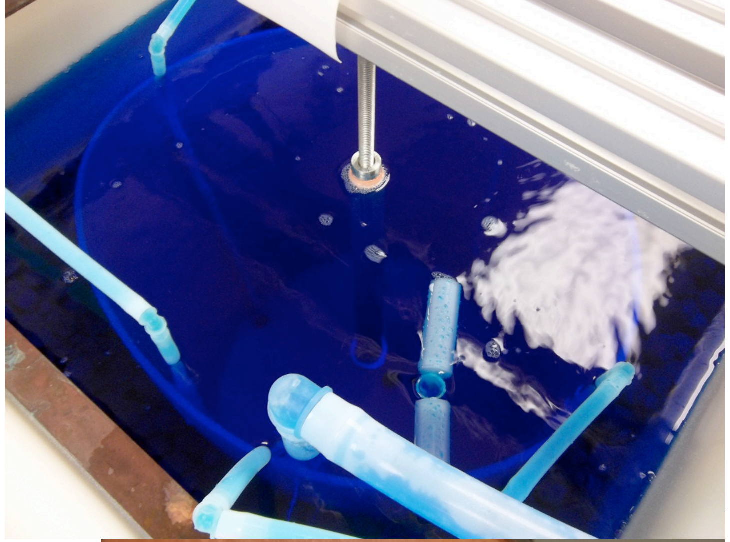




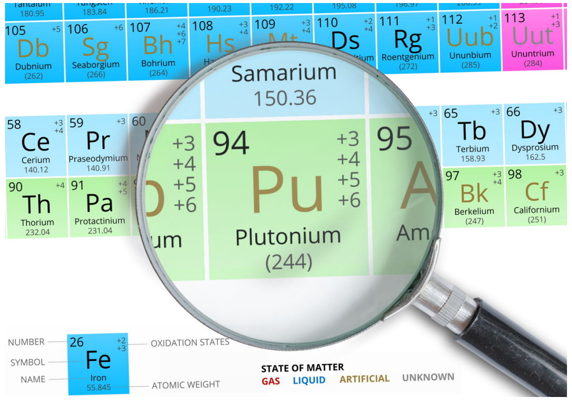
Radioassay of Materials in 0vbb and dark matter searches

Electroformed Cu

- In typical materials U and Th decay-chain contaminants are found at levels of µg/g to ng/g, which produces unacceptable backgrounds.
- Electroforming copper in a carefully-controlled and clean environment allows one to produce copper with U and Th with ultra-low levels.
- Standard conventional assay techniques are far from being able to reach the required sensitivity.



^{244}Pu and Accelerator Mass Spectrometry



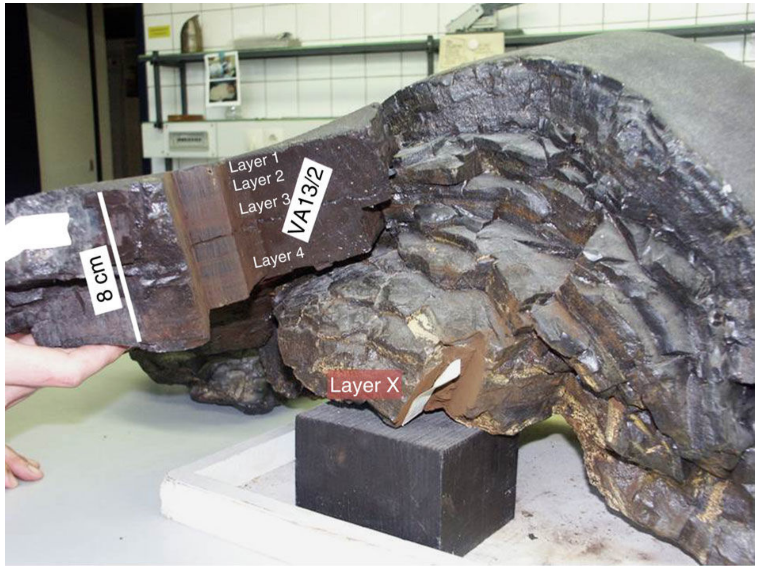
nature COMMUNICATIONS

ARTICLE

Received 30 Mar 2014 | Accepted 26 Nov 2014 | Published 20 Jan 2015 DOI: 10.1038/ncomms6956 OPEN

Abundance of live ^{244}Pu in deep-sea reservoirs on Earth points to rarity of actinide nucleosynthesis

A. Wallner[1,2], T. Faestermann[3], J. Feige[2], C. Feldstein[4], K. Knie[3,5], G. Korschinek[3], W. Kutschera[2], A. Ofan[4], M. Paul[4], F. Quinto[2,†], G. Rugel[3,†] & P. Steier[2]

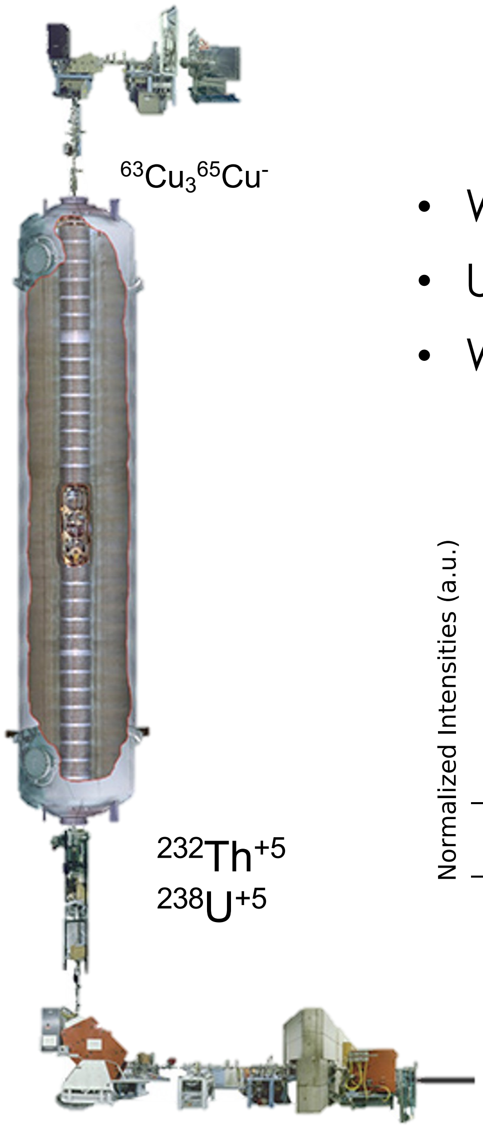


Signal consists of two counts!
Cs-Sputtering source for actinides of the order of 0.1-1% efficiency
Motivation for a more efficient method for trace analysis

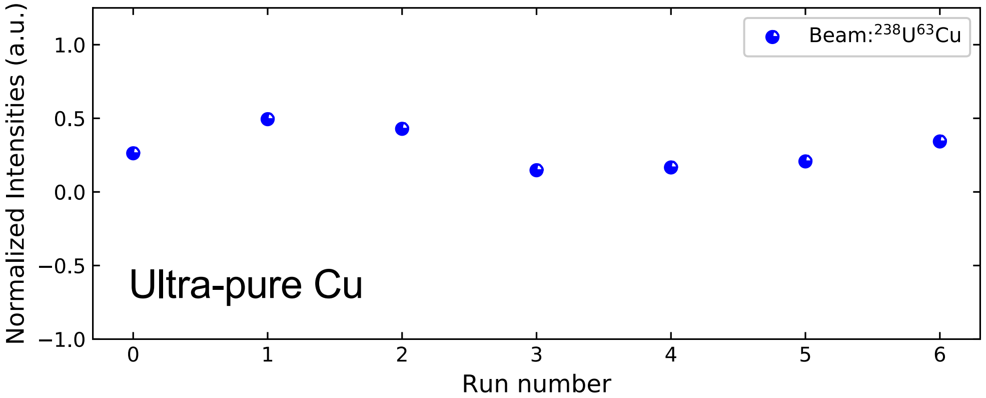
^{244}Pu half-life:
$T_{1/2}$= 80.8 million years

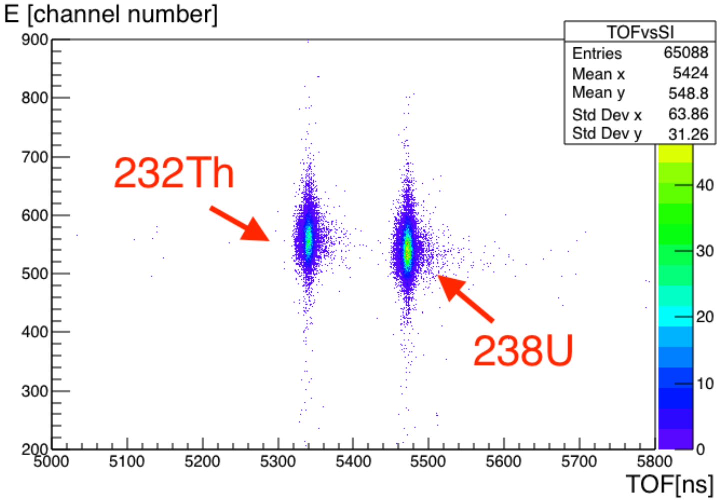
Ultrapure Cu with AMS at ANU

Australian National University



- We tuned the low energy with $^{63}Cu_3{}^{65}Cu$
- Use of charge state +5 and TOF system
- We observed events of Th and U in ultrapure Cu





Cs Sputter source efficiency for actinides 0.01-0.1%

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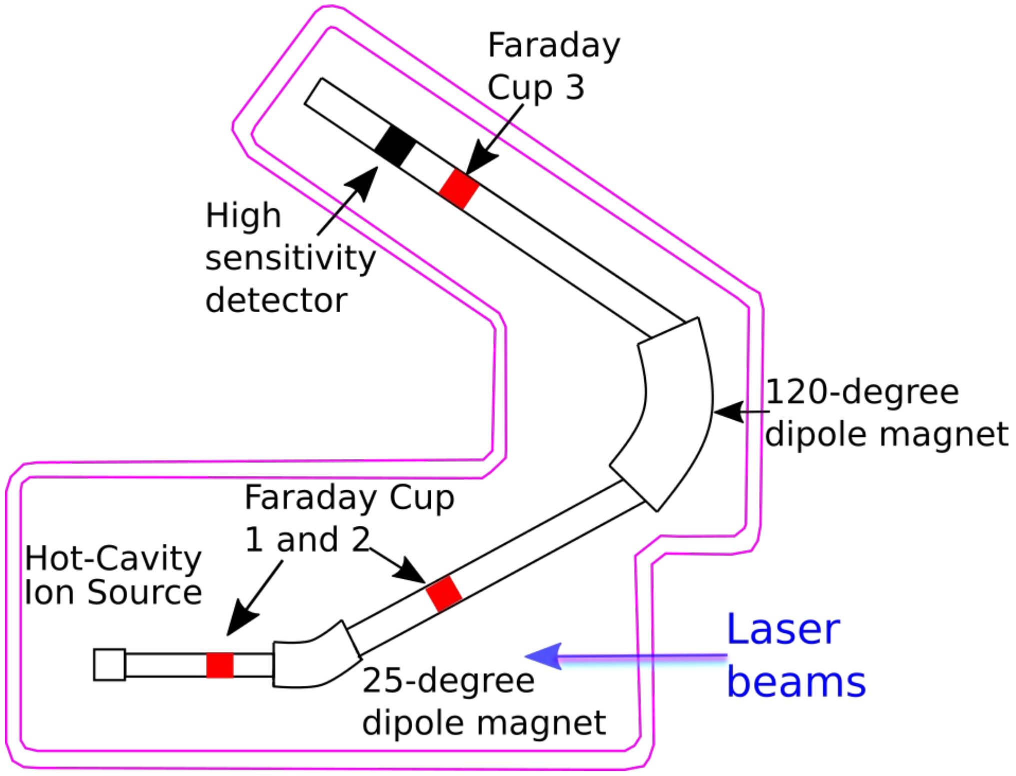
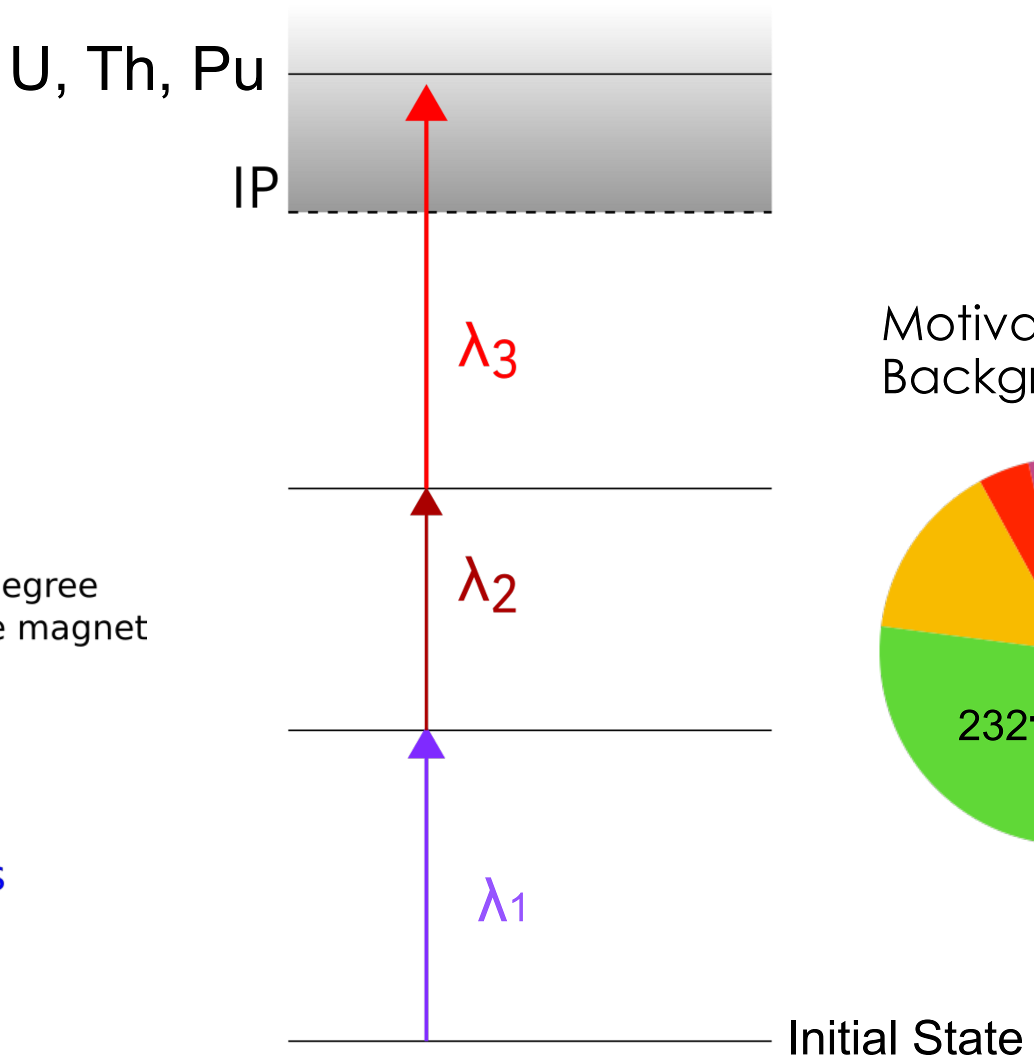
Resonant Ionization Mass Spectrometry

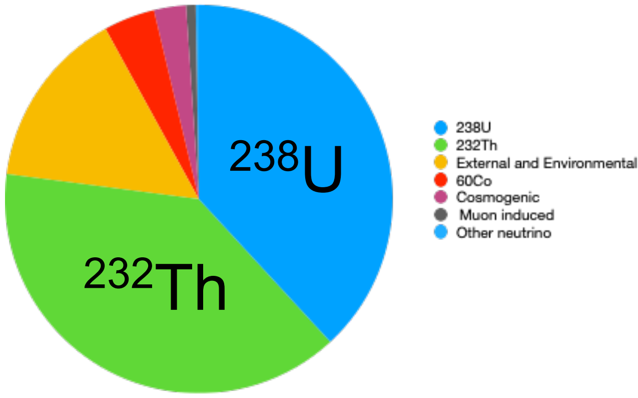
Three Step Resonant Ionization schemes



Sample size : 40 μg



Motivation:
Backgrounds 0νββ



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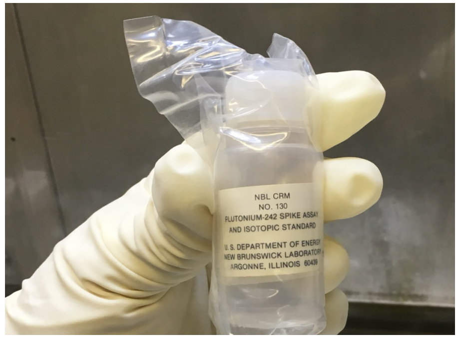
^{242}Pu Sample

1 mg plutonium
30 μCi

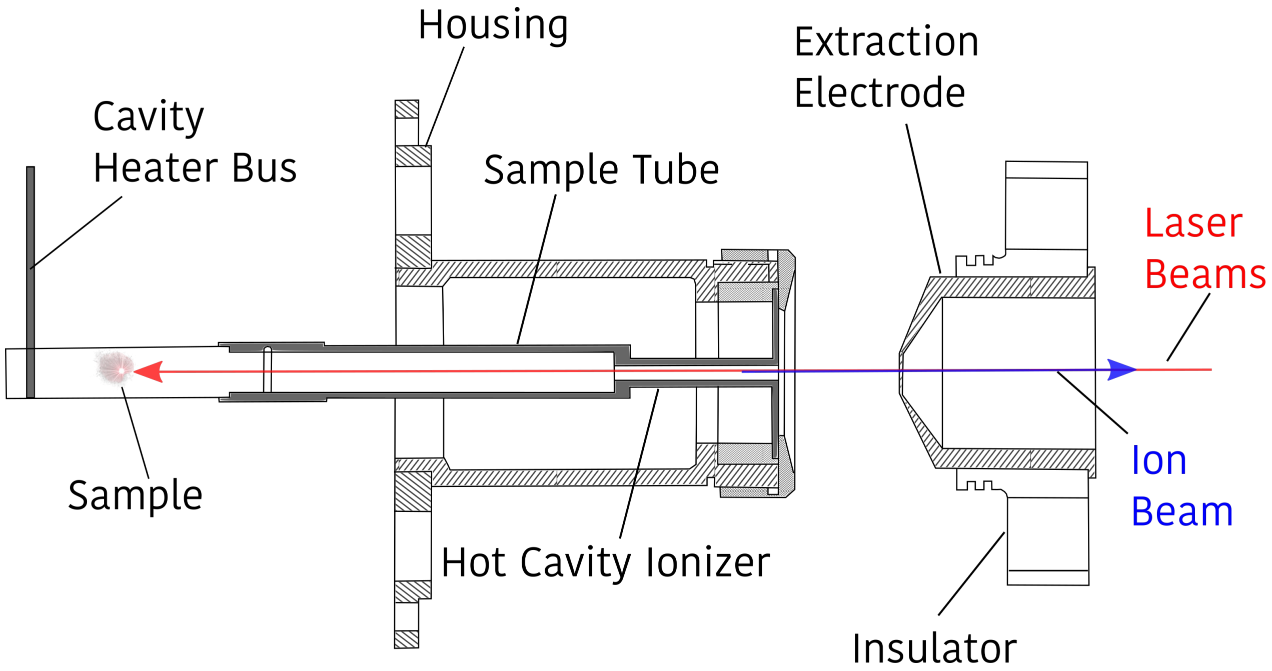


NEW BRUNSWICK LABORATORY

Hot laboratory

Sample wrapped in Zr foil of ~4 x 4 x 0.025 mm

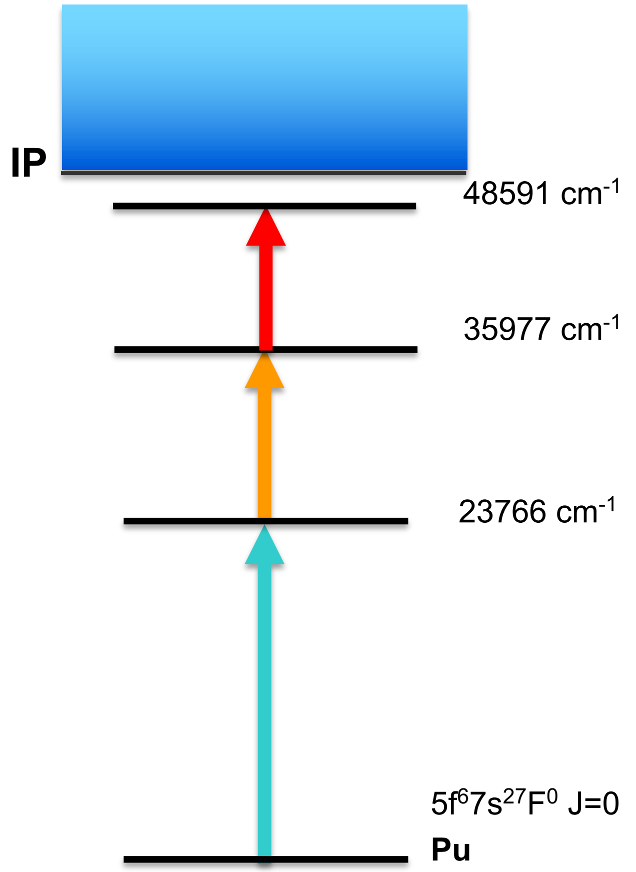
Resonant Ionization Laser Ion Source (RILIS)



Level schemes search
Sample size: 40 μg

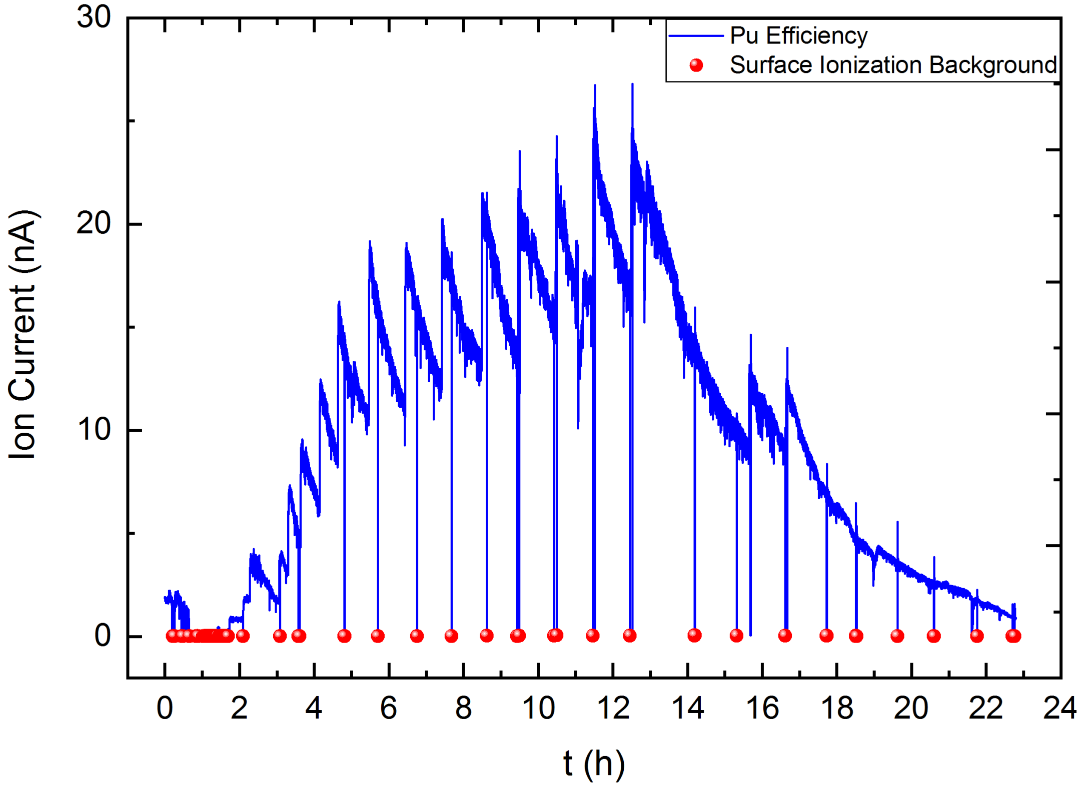
Efficiency Measurement

Measured Efficiency:
51% ± 4% !!

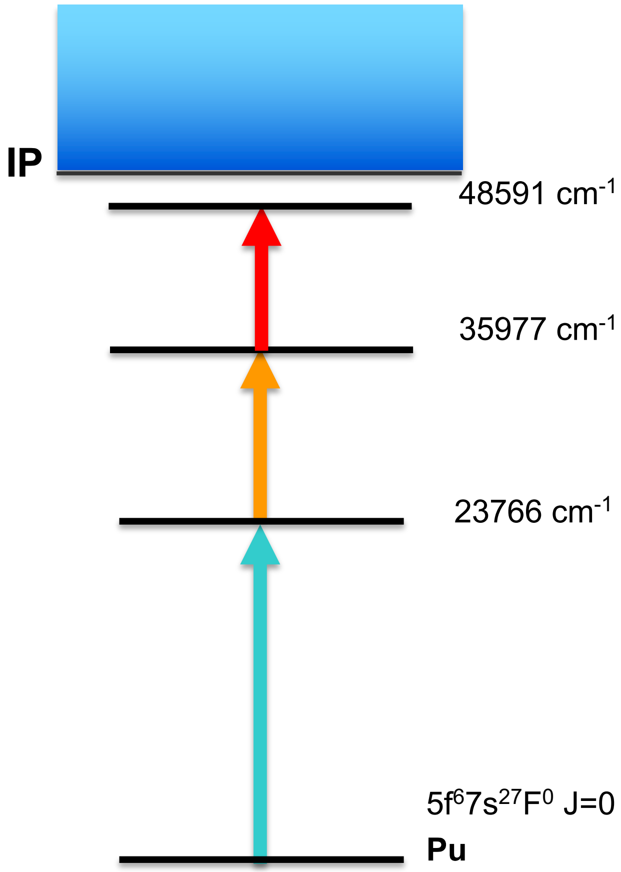


- Sample: 4 μg Pu(10^{16} atoms) wrapped in Zr foil

$$\text{Ionization efficiency} = \frac{\#\text{ of ions detected}}{\#\text{ of neutral atoms in sample}}$$



Sensitivity Measurements for ^{242}Pu

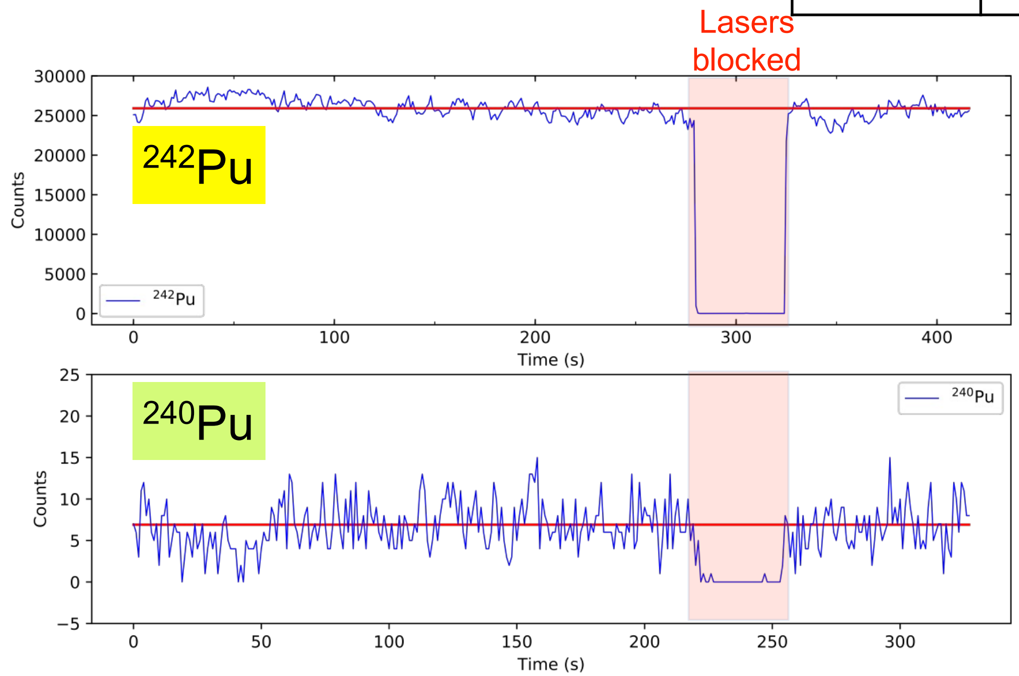


- ^{242}Pu diluted sample to 10 fg (10^{-14} g)

New Brunswick Laboratory
U.S. Department of Energy

Certificate of Analysis
CRM 130
Plutonium-242 Spike Assay and Isotopic Standard in Nitrate Form

Isotope	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{244}Pu
Expected ratio:	4.2E-05	4.8E-05	2.0E-04	2.5E-04	1.0E+00	4.0E-06



Experimental ratio

$$\frac{240\,Pu_{counts}}{242\,Pu_{counts}} = 2.4 \times 10^{-4}$$

Our detection limit is 6×10^3 atoms!

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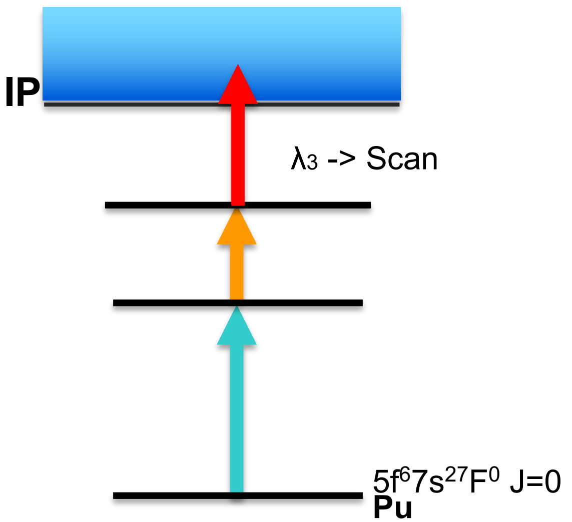
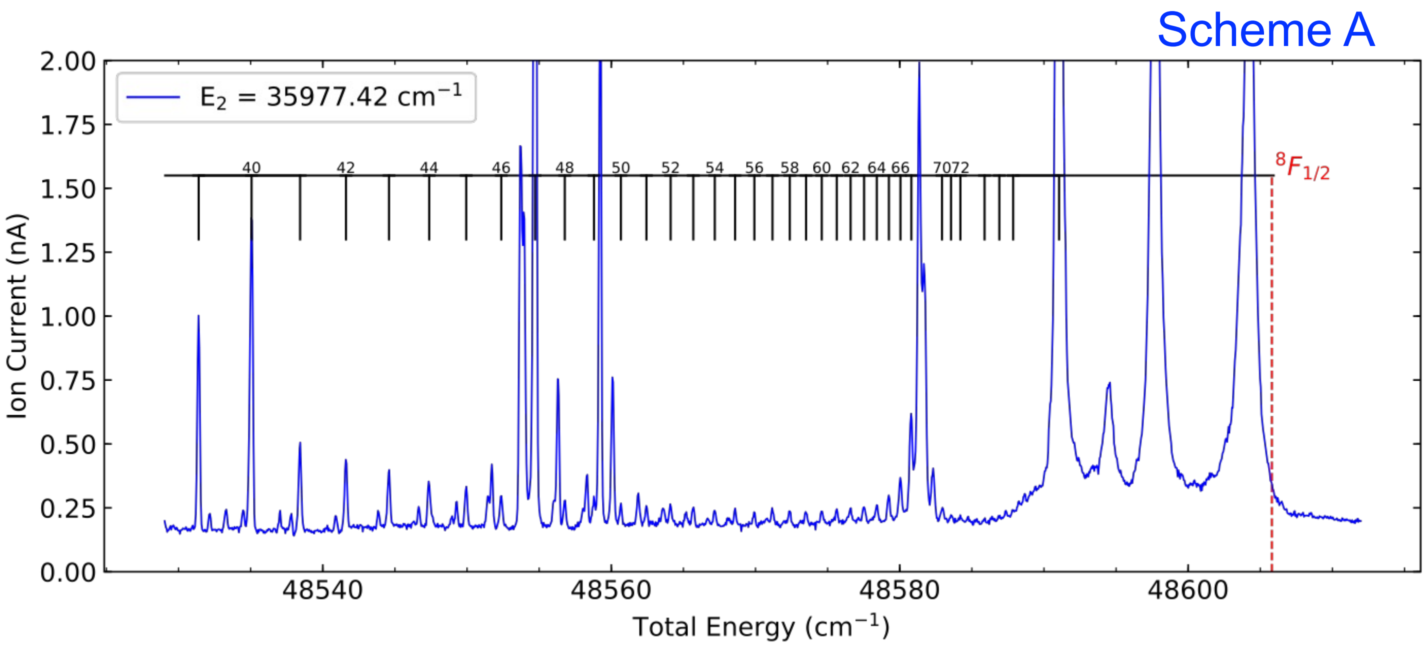
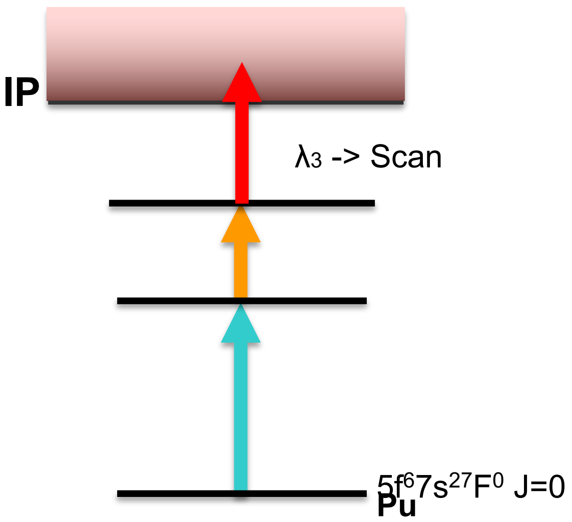
Converging series Rydberg states - IP

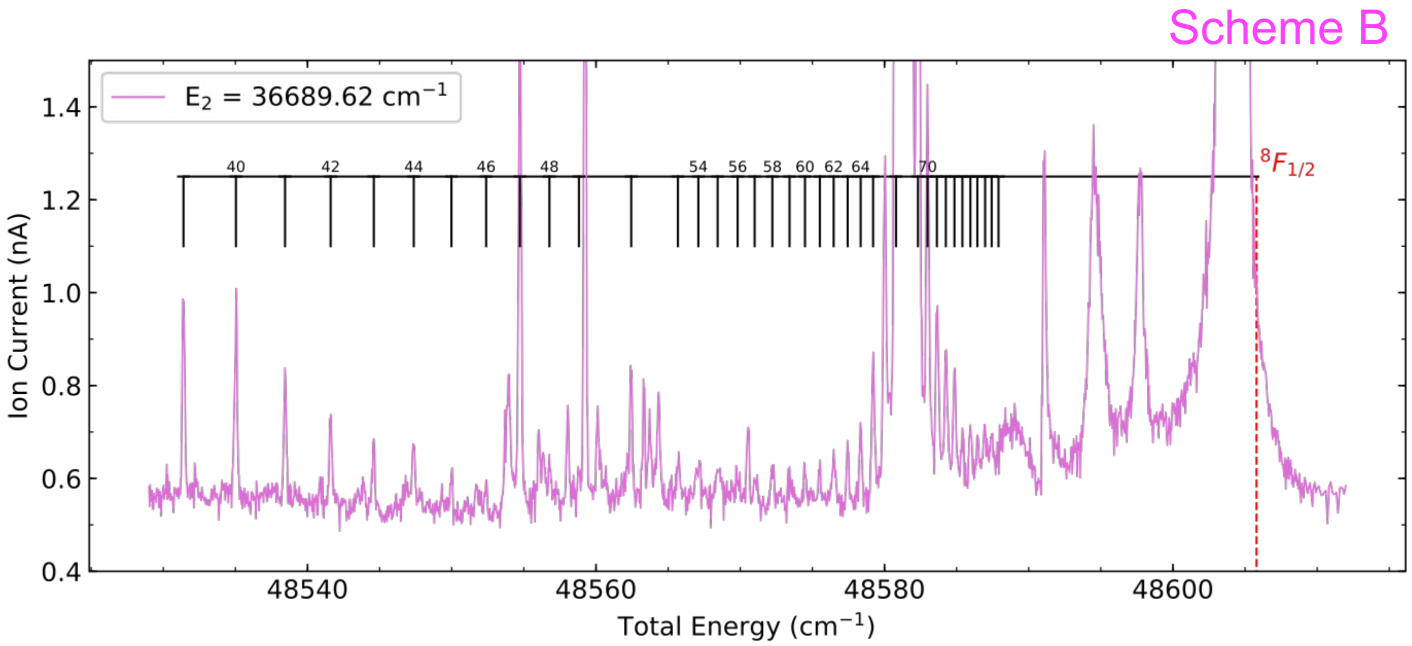
The most precise method for determining IPs is the analysis of the converging series of atomic energy levels with a high principal quantum number *n*, known as Rydberg states. The Rydberg series of an atom can be observed in the ionization spectrum of the final transition of a step-wise resonant ionization scheme.

Observed Rydbergs









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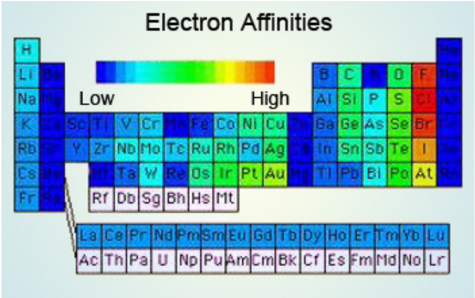
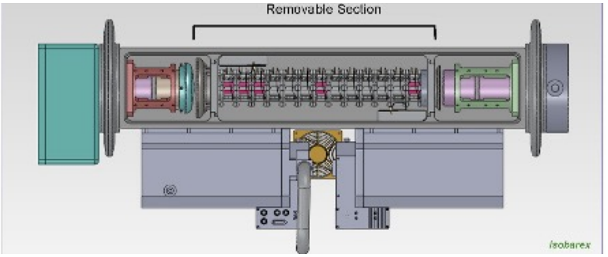
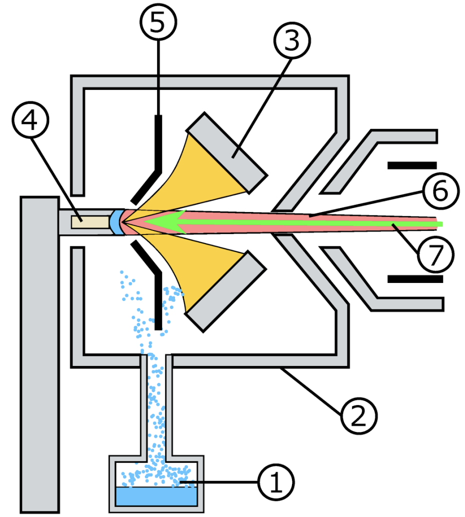
Physical and Chemical methods and techniques in AMS

- Negative atomic ion properties: ~~$^{14}N^-$~~ for $^{14}C^-$, ~~$^{26}Mg^-$~~ for $^{26}Al^-$ and ~~$^{129}Xe^-$~~ for $^{129}I^-$
- Negative molecular ion properties PuF_4^- and UF_5^-
- Fully stripped ions followed by magnetic analysis
- Selective isobar suppression for AMS and RIB science using photodetachment
- Gas-filled magnets
- Projectile HI X-ray emission
- TOF
- dE/dx, range (Bragg detectors, multianode IC, bolometers)
- Selective ion–gas reactions at eV energies in a radio-frequency quadrupole cell to selectively attenuate both atomic and molecular isobars (IsoTrace; Isobarex)
- LASIS: The laser assisted sputter ion source
  - John S. Vogel (LLNL-AMS), NIM 438 (2019)
  - O. Tarvainen, et al., (Jyvaskyla) J. Appl. Phys. 128 (2020) 094903







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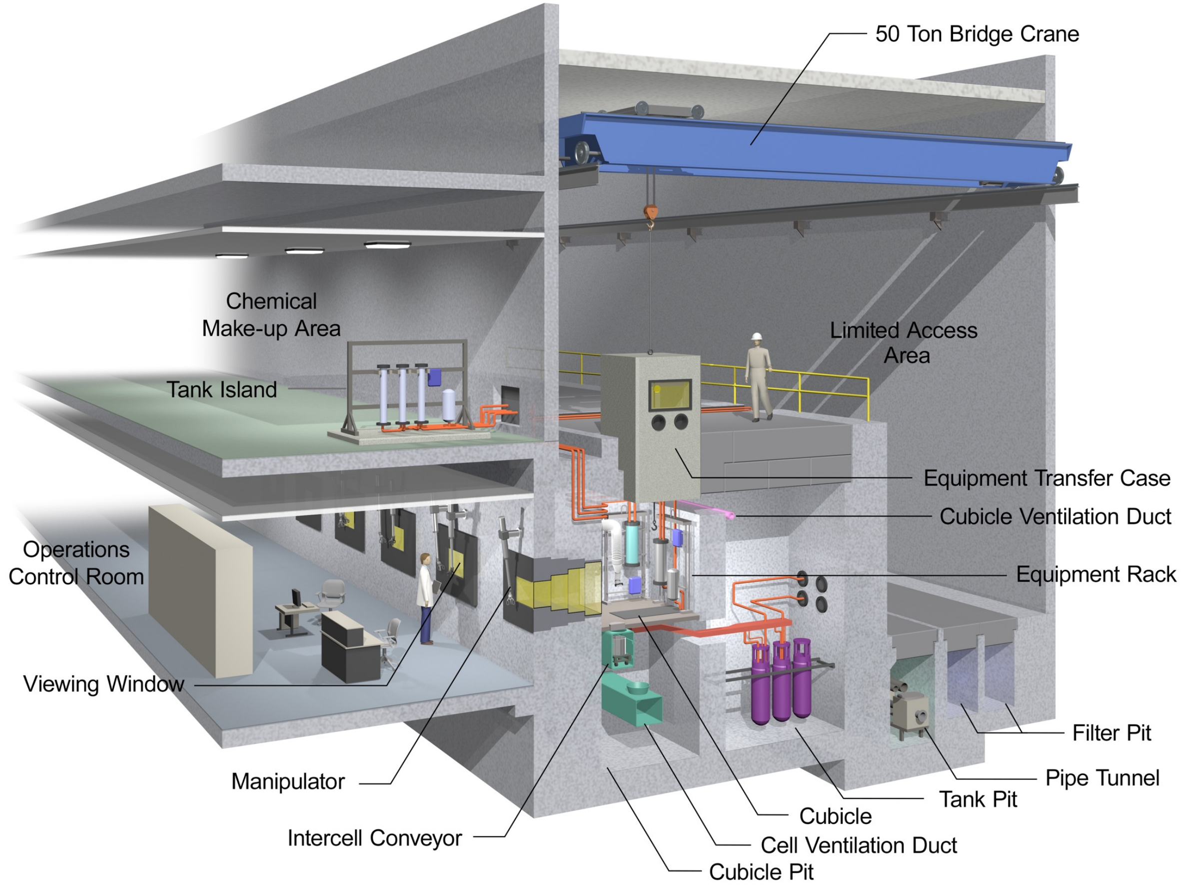
HFIR and REDC enable heavy element production at ORNL

- HFIR and REDC began operation in 1965 and 1966
- Operation is expected to continue at least until 2040
- High-end aspects of isotope production (heavy actinides, specialty medical isotopes), neutron scattering, and materials irradiation
- Unique capabilities for radioisotope separations (>400 isotope shipments annually to universities, hospitals, industry, and other research institutions)

Radiochemical Engineering Development Center

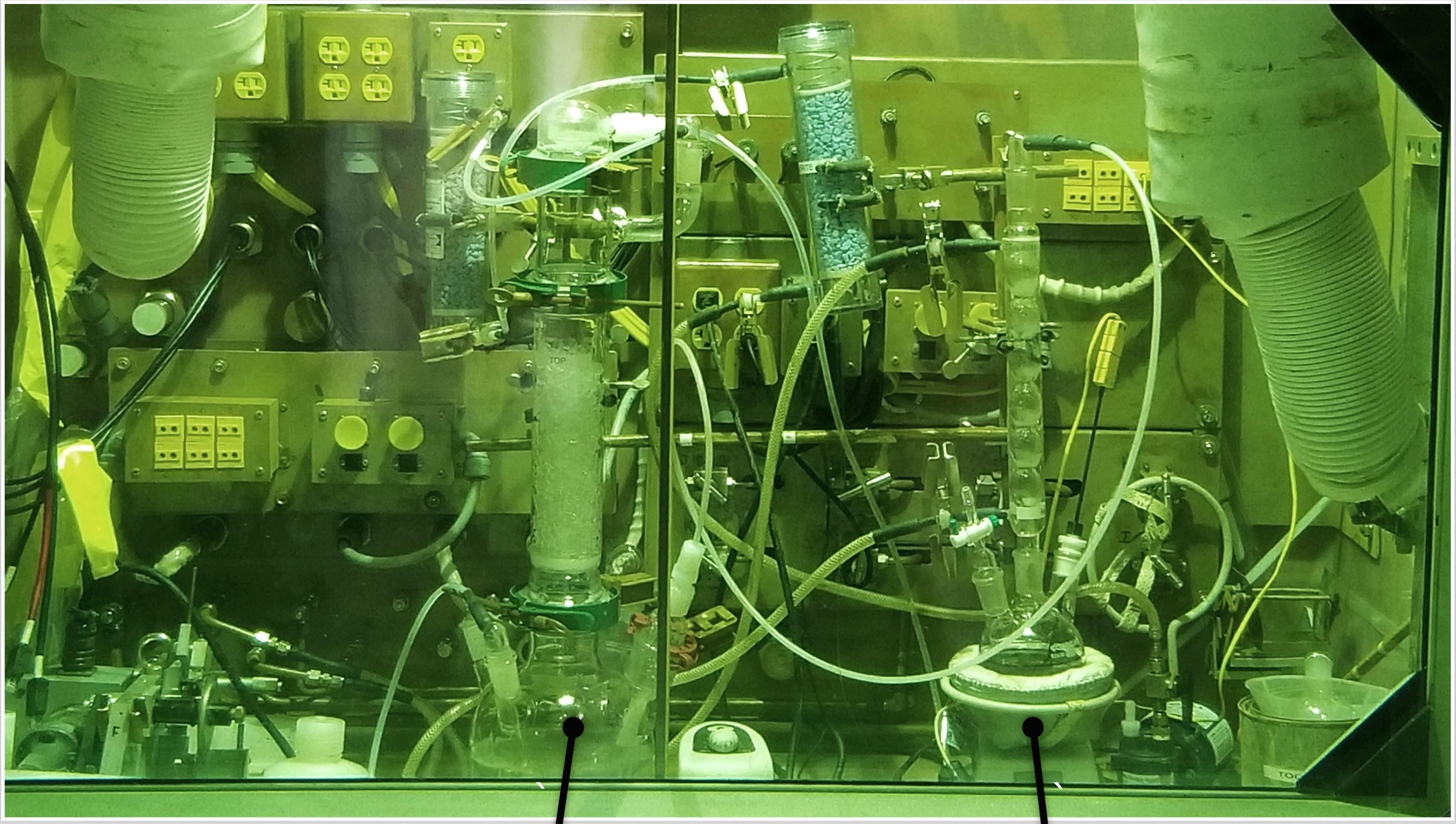
Unique capabilities for radiochemical processing and related R&D

- Heavily shielded hot cells for radiation control and alpha containment
- Shielded caves for radiochemical processing and R&D
- Glove box labs for final product purification and R&D
- Radiochemical labs for sample preparation and analysis
- Cold labs for chemical make up, cold testing, and target fabrication



REDC is fully utilized for research and production for industrial, medical, and research partners

Shielded cave set up for dissolution



Base bath system

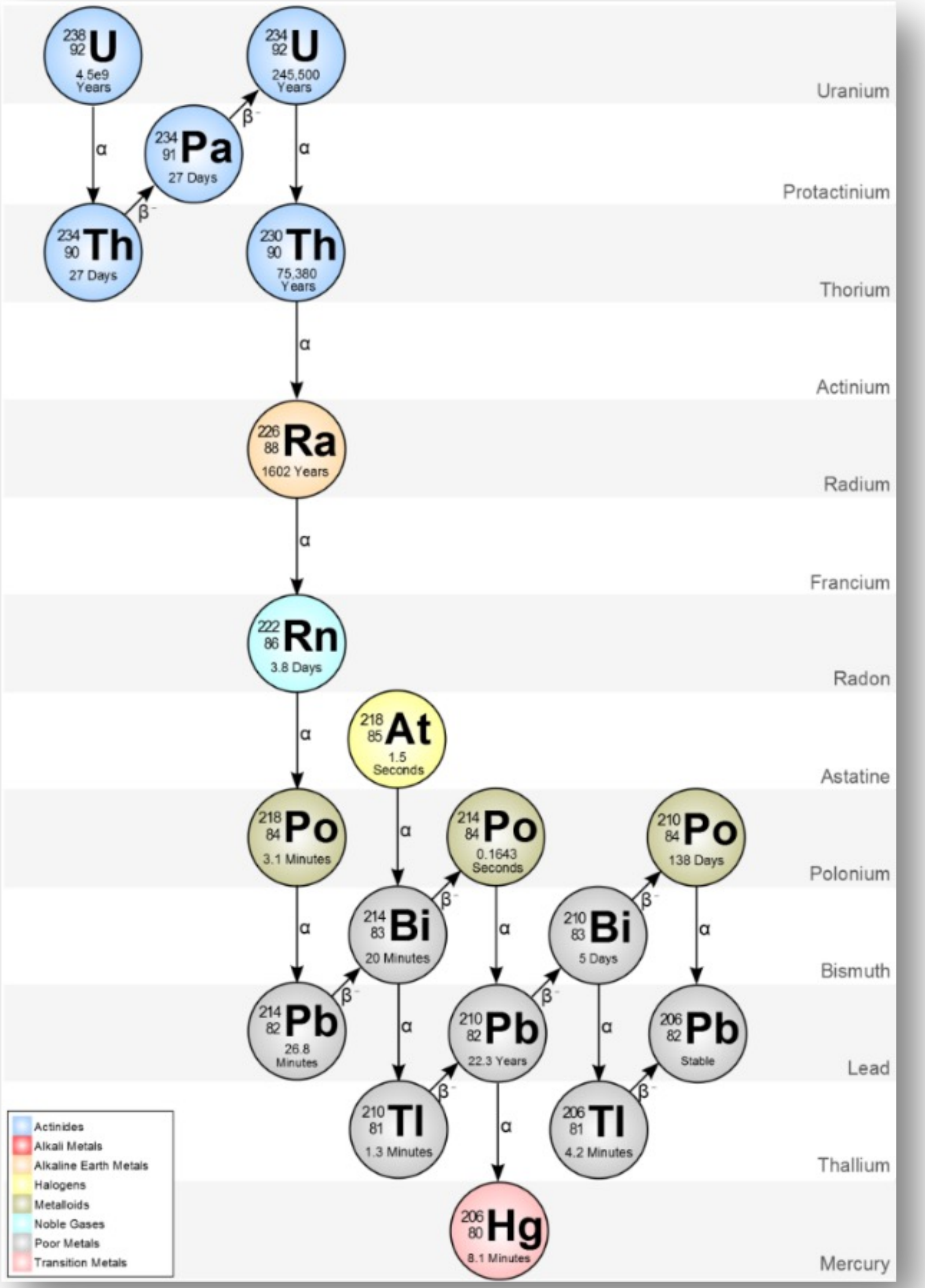
Round bottom flask,
heating mantle,
and reflux condenser

^{226}Ra handling/processing at ORNL

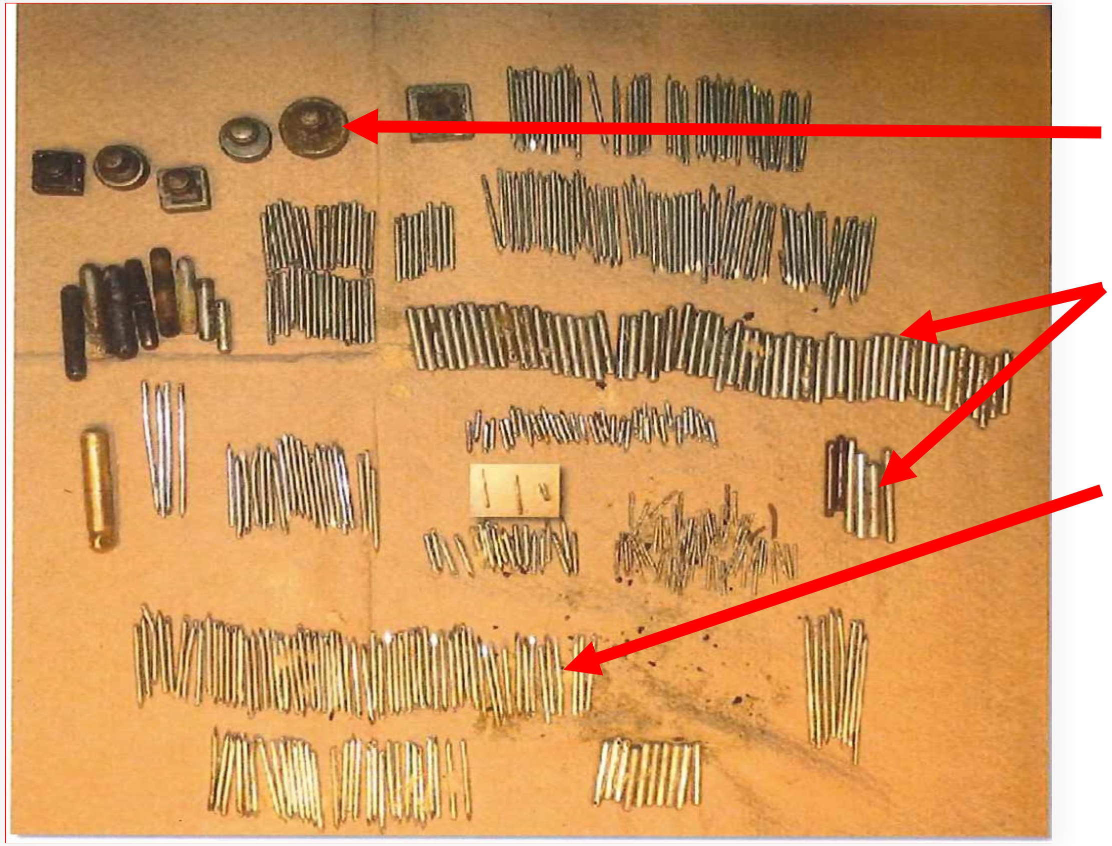
- In 2016, ORNL started a focused effort to recover ^{226}Ra from legacy medical devices (waste items)
  - The recovery and purification of ^{226}Ra is performed in hot cells located at ORNL
  - This material is used mainly for production of medical isotopes at HFIR (^{228}Th and ^{227}Ac)
- ^{226}Ra is available from the DOE Isotope Program (isotopes.gov)
- ^{226}Ra has also been used at ORNL for other experiments
- The ORNL team has experience with packaging ^{226}Ra salts (nitrate or carbonate) for transfer on-site and for off-site transportation

^{226}Ra and the ^{238}U Decay Chain

- ^{226}Ra is a decay product of ^{238}U
- Long half life ($t_{1/2}$ = 1600 years)
- Decays by alpha emission to ^{222}Rn ($t_{1/2}$ = 3.8 days)
- ^{222}Rn subsequently decays by alpha/beta emission via short-lived daughters to ^{210}Pb
- Radon is a gas and contributes to emissions from this process
- The exhaust stack is monitored and emissions are reportable



Legacy Radium Medical Devices

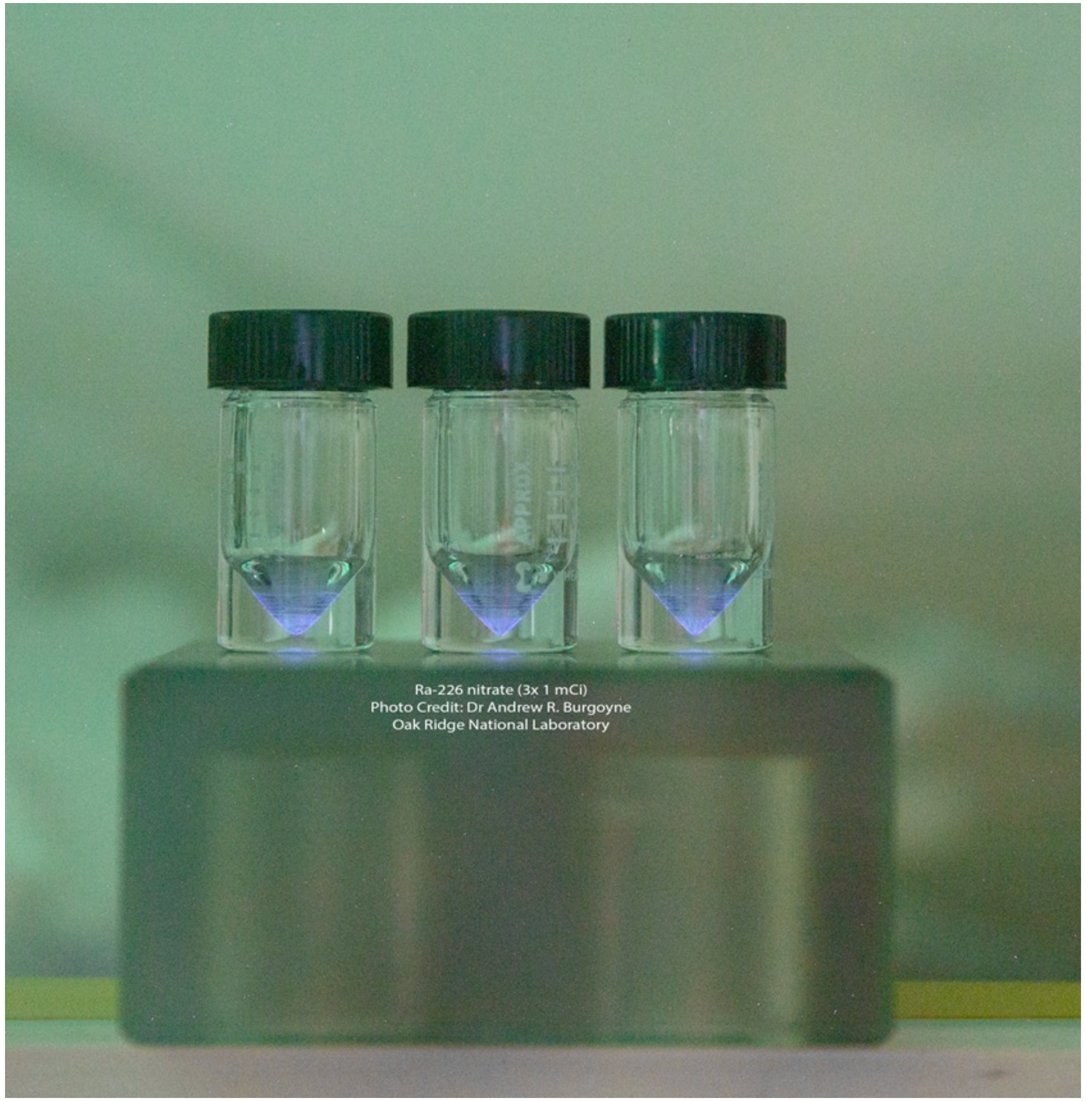


Sources contain various amounts of ^{226}Ra (1 mCi up to 100 mCi)

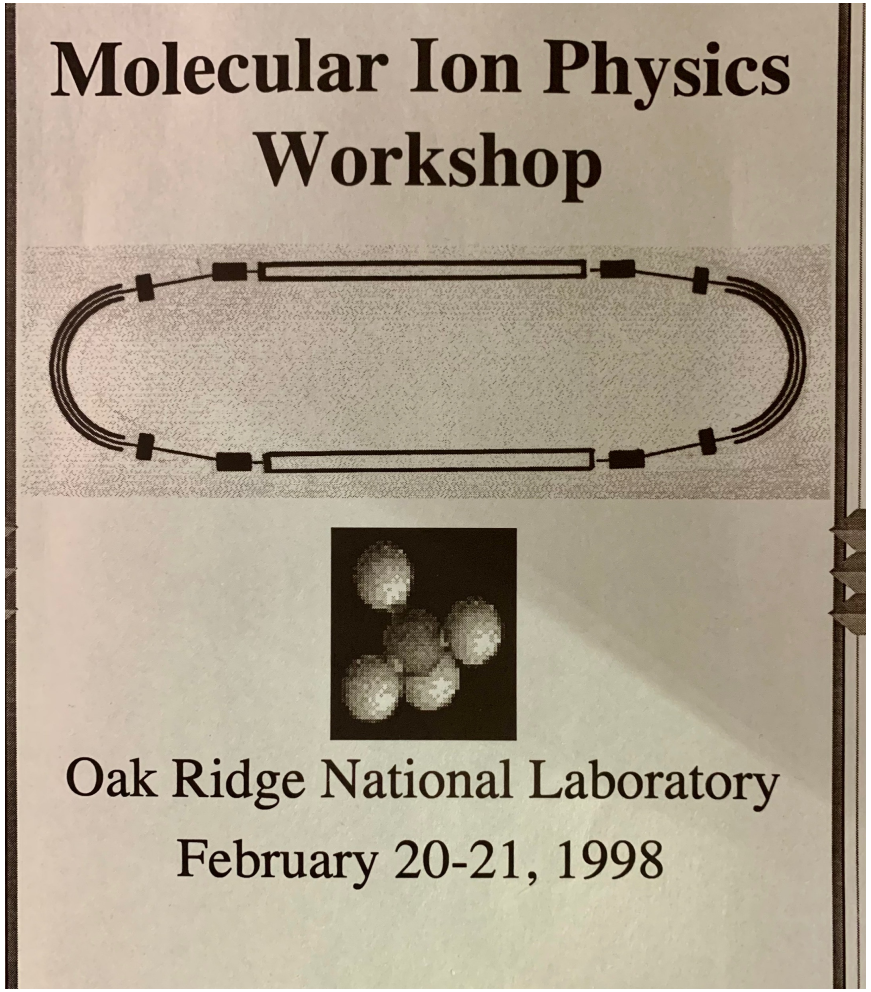
Devices are mechanically opened, and radium is chemically dissolved from the fragments

^{226}Ra purification is performed in a hot cell facility at ORNL

Cherenkov radiation from dispensed ^{226}Ra in glass vials (1 mCi each)

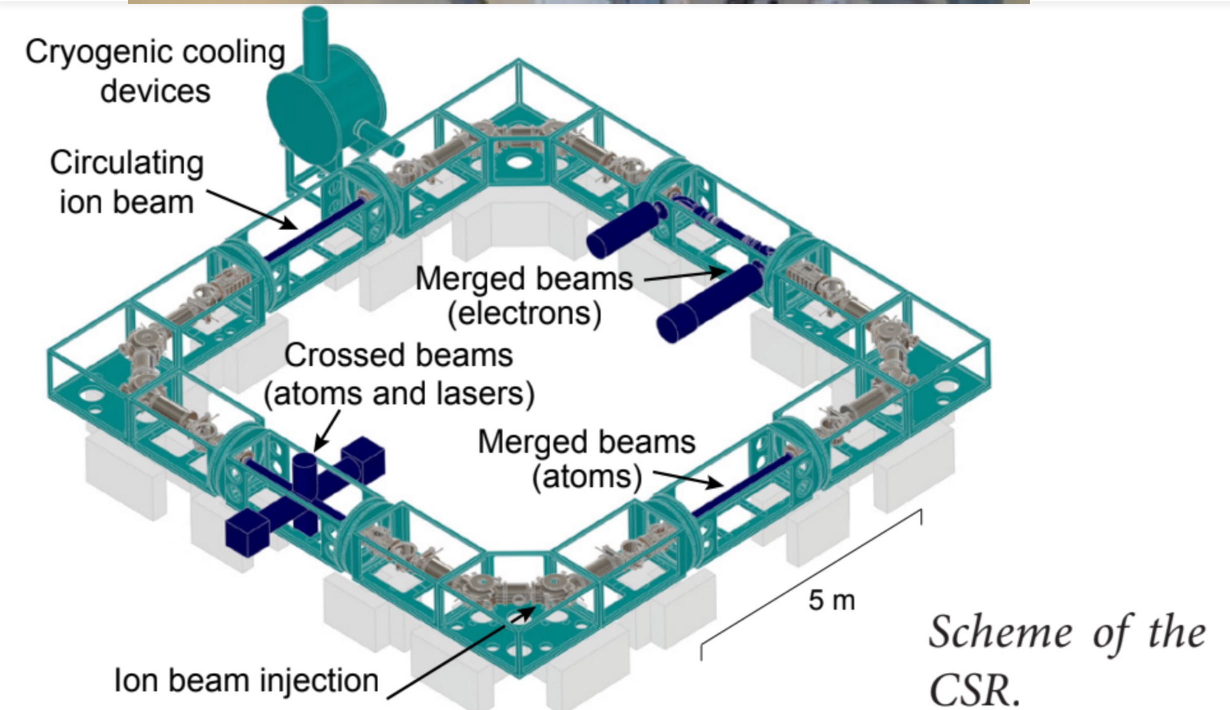


Use of Electrostatic Rings ?



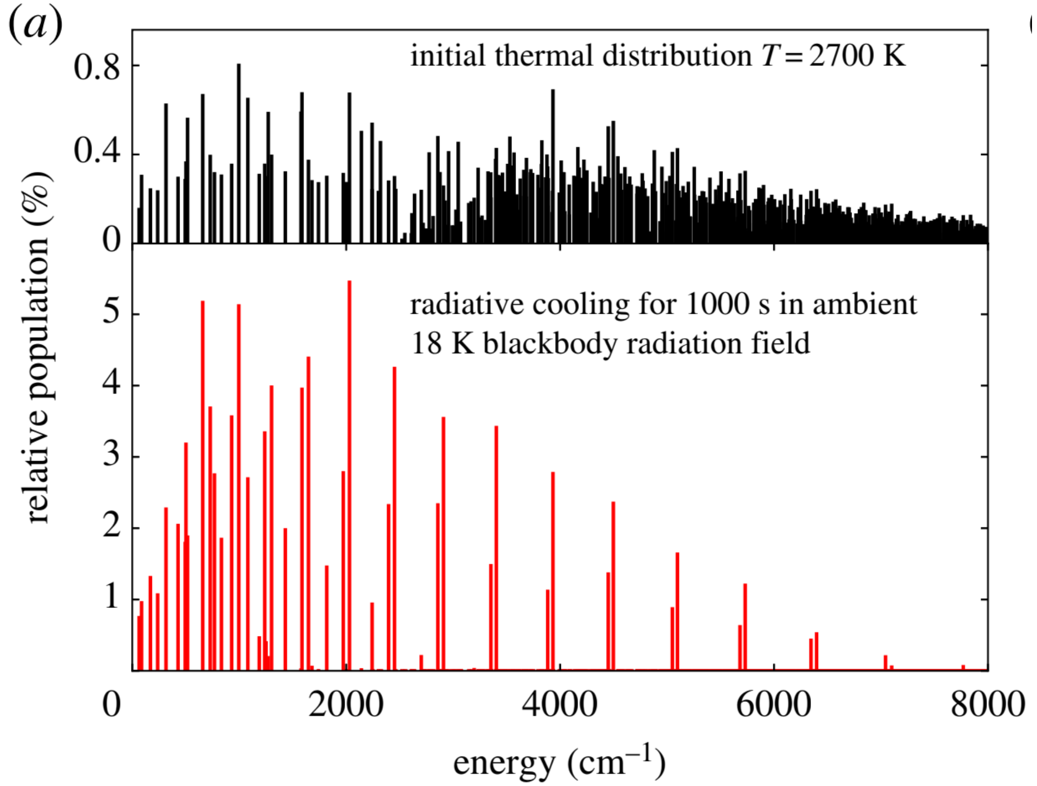
ELISA
Aarhus

CSR
Heidelberg



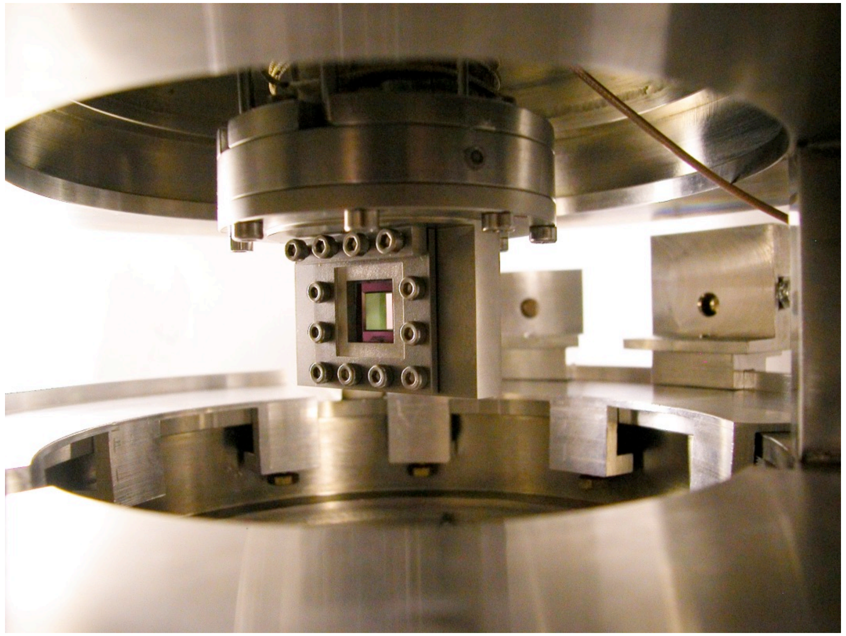
Scheme of the CSR.

Astrophysical interest in H_3^+



- The triatomic hydrogen ion still poses great experimental challenges.

Polarized Targets for RIBs – ORNL/PSI



- Dynamic Nuclear Polarization Technique
- Thickness ~ 0.1 - 20 mg/cm^2 Polystyrene
- Low temperatures : T = 225 mK ,
- High Magnetic Fields : B = 2.5 T

Juan Pablo Urrego-Blanco Ph.D. UTK

Shell Oil Chairman's Award 2017

Target is contained in a superfluid helium leak tight cell with 500 nm thick Si_3N_4 windows.

Polarization is sampled in real time with an NMR coil attached to the target.

Proof of Principle at PSI (Switzerland) using elastic scattering:

$$\vec{p}\left({}^{12}C,{}^{12}C\right)p \quad \text{at} \quad 38\,\text{MeV}$$

J.P. Urrego-Blanco *et al.*, Nucl. Instr. and Meth. **B 261** (2007) 1112

CONCLUSIONS

Demonstrated a method to detect Th and U in ultrapure Cu using AMS

Established the highest efficiencies on Th, U and Pu and the highest sensitivity using RIMS

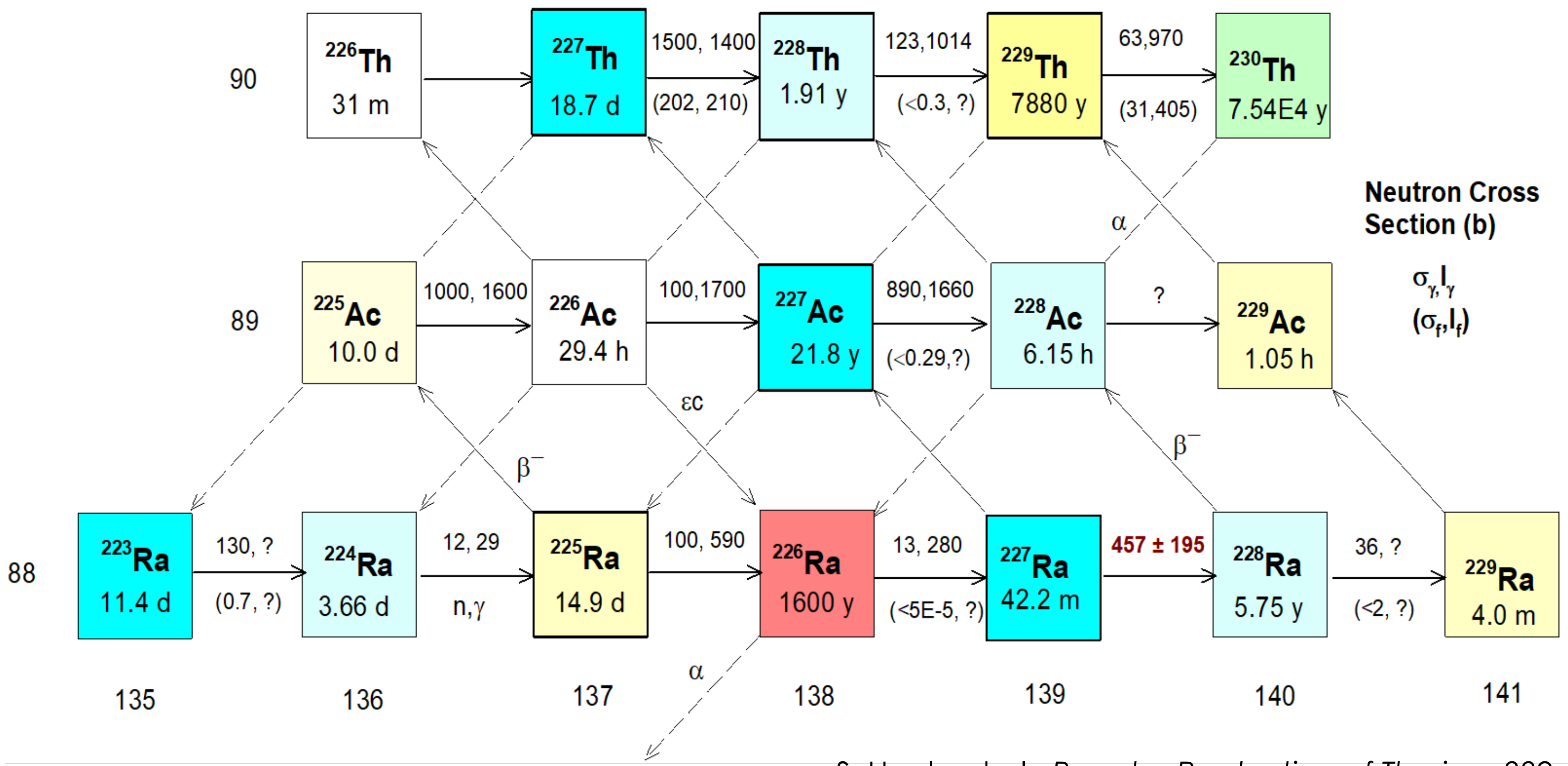
Determined a new value of IP for plutonium significantly more accurate than the NIST value

Summary

- Heavy nuclei with static octupole deformations, such as Fr, Ra, Th, Pa, and others, can have hadronic CP violation sensitivity enhancements up to a thousandfold larger than spherical nuclei. Combined with relativistic enhancements from their high mass, molecular species with deformed nuclei can be up to 10^6 times more intrinsically sensitive than the current atomic Hg, which is the most sensitive atomic or molecular hadronic CPV experiment.
- Efficient and ultra-sensitive analysis of actinides for underground physics
- Spectroscopy studies to search for efficient ionization schemes for U, Th and Pu using RILIS
- Overall efficiency of 51% for Pu, 40% for Th and 9% for U was obtained by RILIS
- We demonstrated that RIMS is a highly selective powerful method that meet the requirements for ultra-trace detection having a high efficiency and the required sensitivity
- We established a new value for the ionization potential of plutonium with two analysis methods.
- Studied formation of molecules and large clusters of atoms
- ORNL has the radiochemical expertise to handle actinides safely
- 226Ra and 225Ra could be available for research…

^{226}Ra is important for the DOE Isotope Program

- This shows the network of isotopes produced at HFIR during irradiation of a ^{226}Ra target – this is a valuable feedstock for production of alpha-emitting radioisotopes, including ^{229}Th, which decays to ^{225}Ra
- ORNL is uniquely qualified for large scale processing and irradiation of ^{226}Ra targets



S. Hogle et al., *Reactor Production of Thorium-229*, Appl. Radiat. Isot. 114, 19 (2016)