Nuclear structure and astrophysics investigations at TRIUMF-ISAC

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Nuclear Reactions: A Symbiosis between Experiment, Theory and Applications
INT Workshop, University of Washington, Seattle
TRIUMF was founded in 1968 and has delivered nearly 50 years of accelerator-based science and innovation for Canada, and is engaging the World.
TRIUMF’s accelerator complex

Nordion commercial medical isotope production
3 cyclotrons

Cyclotron
500 MeV
350 μA

Particle Physics
Pienu
Ultra Cold Neutrons

CMMS
Centre for Molecular and Material Science (μSR)
TRIUMF’s accelerator complex

40 MV SRF Heavy Ion Linac

ISAC-I
60 keV, 1.7 AMeV

ISAC-II
>10 AMeV

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

Nordion
commercial medical
isotope production
3 cyclotrons

Cyclotron
500 MeV
350 μA

Particle Physics
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Ultra Cold Neutrons

CMMS
Centre for Molecular and Material Science (μSR)
TRIUMF’s accelerator complex

- **ISAC** (Isotope Separator and ACcelerator)
  - Rare Isotope Facility
  - Nuclear Structure
  - Nuclear Astrophysics
  - Fund. Symmetries
  - CMMS ($\beta$NMR)

- **Nordion**
  - Commercial medical isotope production
  - 3 cyclotrons

- **eLINAC**
  - 35 MeV
  - 100 $\mu$A

- **Cyclotron**
  - 500 MeV
  - 350 $\mu$A

- **Particle Physics**
  - Pienu
  - Ultra Cold Neutrons

- **CMMS**
  - Centre for Molecular and Material Science ($\mu$SR)

**Advanced Rare Isotope Laboratory (ARIEL)**

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

- **ISAC-II**
  - $>10$ AMeV

- **40 MV SRF Heavy Ion Linac**

- **Heavy Ion Linac**
  - 350 $\mu$A

- **500 MeV Linac**
  - 3 AMeV

- **40 MV SRF Linac**
  - 6 AMeV
ISOL facility with **high primary beam intensity** (100 $\mu$A, 500 MeV, $p$) Delivering RIBs since 1999.

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

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

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

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Isotopes delivered at ISAC (Updated June 2016)

Target materials: SiC, TiC, NiO, Nb, ZrC, Ta, U
Ion sources: Surface, FEBIAD, IG-LIS
Low energy RIBs < 60 keV

**ISAC experimental areas**

- **FRANCIIUM MOT**
  (PNC, anapole moment)

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

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

- **Polarizer beamline**
  Laser spectroscopy, MTV
  CPT test, betaNMR

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

- **Beta-NMR**
  Material science

INT Workshop
Medium energy RIBs
~ 0.15 - 1.7 AMeV

**TUDA**
Astrophysical charged particle reactions

**DRAGON**
Astrophysical capture reactions
High-energy RIBs > 6 AMeV

EMMA (2017) Mass analyzer for nuclear reactions

IRIS Solid hydrogen target for direct nuclear reactions

TIGRESS + auxiliary detectors
HPGe $\gamma$-ray spectrometer in-beam spectroscopy of nuclear reactions

TUDA Scattering array for direct reactions
Experimental facilities and programs of ISAC

TITAN Penning Trap facility

EMMA recoil mass analyzer

Nuclear Structure

Nuclear Astrophysics

Fundam. Symmetries

Material Science

Laser polarizer line

Francium trapping facility

TRINAT magneto optical trap

DESCANT

GRIFFIN

MTV Mott scattering drift chamber

TIGRESS in-beam gamma-ray spectrometer

IRIS solid hydrogen reaction set-up

DRAGON recoil separator

TUDA reaction setup

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

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

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

**WHY:**
- to explain what holds atomic nuclei together
- a full understanding of the nuclear strong force
• Transmission ion chamber for beam identification
• Frozen gaseous target on thin Ag foil
• Si and CsI detectors for particle identification and angular distributions
First evidence of a dipole resonance in $^{11}\text{Li}$ having an isoscalar character.

Provides stringent tests of \textit{ab initio} theories and nuclear forces.
TUDA array
1pnA $^{26}\text{Al}$ at 6 AMeV with GS/IS=17,000/1
~50 μg=cm$^2$ thick CD$_2$ target
~40keV FWHM

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

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

G. Hackman & C.E. Svensson, Hyperfine Int. 225, 251 (2014)
BAMBINO: Collaboration with Lawrence Livermore Nat's Lab, U. of Rochester
- 2 Si detectors for heavy-ion detection, TIG-10 readout
- Well suited to Coulex

SHARC Silicon Highly-segmented Array for Reactions and Coulex
- U. York-LSU-CSM*-TIGRESS collaboration
- High granularity, full angular range coverage, dE-E telescopes, TIG-64 readout

\[ C.A. \text{ Diget et al, J. Inst.} \textbf{6, P02005 (2011)} \]

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

\[ G.L. \text{ Wilson et al, J. Phys. Conf.} \textbf{381, 012097 (2012)} \]
$^{11}\text{Be}$ at 31.2 and 39.6 MeV
- $^{197}\text{Au}$ 1.9 mg/cm$^2$ target
- Coulomb barrier $\sim$40 MeV

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

- HPGe: 12 clovers, 90 and 135 deg, high suppression mode
V. Pesudo, M.L.G. Borge et al., Accepted to PRL.

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

$\Delta E$-$E$ from single 3x3mm$^2$ pixel

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

$^{10}$Be
29.6MeV
$\theta$=18°

$^{11}$Be
39.6MeV
$\theta$=18°

Doppler-corrected for $^{11}$Be

Uncorrected 279keV $^{197}$Au 320keV $^{11}$Be
Structure of $^{11}$Be:
- (SP) Single Particle
- (CEX) Particle-plus-core model

Scattering observables:
- (EPM) Equivalent Photon Method (SP)
- (CDCC) Continuum-Discretized Coupled Channels (SP)
- (XCDCC) CDDC with core-halo entanglement (CEX)
B(E1) strength calculation – coupling of core and halo states is important

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

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

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

Other TIGRESS data: $^{11}\text{Be}(p,d)@110\text{ MeV}$ and $^{11}\text{Be}(^{9}\text{Be},x)@30, 55\text{ MeV}$
Nuclear astrophysics aims at understanding the origin of all stable isotopes as observed in the “solar abundance curve”

“Heavy element nucleosynthesis” summarizes several reaction mechanisms producing all elements heavier than Fe:
- “slow” neutron capture process
- “rapid” neutron capture process
- “intermediate” neutron capture process
- Production of proton-rich isotopes

\[ N_\odot = N_s + N_r + N_i + N_p \]
### Direct Capture Cross Section measurements at DRAGON

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

**7 RIB**

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

$^{19}\text{F}$ observed in nova ejecta

→ Direct comparison of experimental results with astronomical data!
→ Probe nucleosynthesis models!

$^{19}\text{F}$ is only stable fluorine isotope

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

→ Fluorine observed in ejecta exclusively from $^{19}\text{F}$ contribution
Experimental determination of reaction rates → nova models

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

- High uncertainty in reaction rate
- Rate variations may affect $^{19}$F abundance by up to a factor of 7! [2]
  → Essential to constrain uncertainty!
• $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$ reaction rate dominated by single low-energy resonance at $E_R \sim 457$ keV above proton threshold (2190.1(11) keV) in $^{20}\text{Na}$

• Direct experimental determination of → Probe for theoretical models

BUT:
Exact resonance strength and $J^\pi$ have been subject to debate for 2 decades!

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

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Analysis in progress! (Collaboration with University of Surrey)

- **Black**: Raw singles events
- **2 main clusters**: $^{19}$F & $^{19}$Ne

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

457 keV resonance likely **stronger** than previous upper limit!
First experimental measurement of this reaction rate.

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

First charge-bred beam to DRAGON. Heaviest RIB direct radiative capture measurement.
Installation of the Electromagnetic Mass Analyzer EMMA completed in TRIUMF’s ISAC-II experimental hall just in time for December 16th, 2016 beam time.

Designed to spatially separate reaction products from beam, disperse them according to mass/charge; focuses products in angle and energy.
Successful Initial Test of EMMA

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

![EMMA’s First Mass/Charge Spectrum](image)

$^{36}\text{Ar}^{13+}$
FWHM = 5.6 mm
M/Q Resolving Power = 170

$^{36}\text{Ar}^{14+}$
**GRiffin**: Sensitive Decay Spectroscopy

Fast, in-vacuum tape system 
*Enhances decay of interest*

**SCEPTAR**: 10+10 plastic scintillators 
Detects beta decays and determines branching ratios

**ISOBAR** 
*Longer* T_{1/2} 
*Shorter* T_{1/2}

**J^π_{ISOMER}**

**J^π_{GS}**

**Zero-Degree Fast scintillator** 
Fast-timing signal for betas

**LaBr_3**: 8 LaBr_3 
Fast-timing of photons to measure level lifetimes

**PACES**: 5 Cooled Si(Li)s 
Detects Internal Conversion Electrons and alphas/protons

**HPGe**: 16 Clovers 
Detect gamma rays and determines branching ratios, multipolarities and mixing ratios

**DESCANT Neutron array** 
Detects neutrons to measure beta-delayed neutron branching ratios

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

4096 crystal pairs at 52 unique angles for γ-γ angular correlations
Two previous beta decay experiments from the 1960’s

M. Yagi et al., Laboratory Nucl. Sci., Tohoku Univ. 1, 60 (1968).
$^{46}$Ca level scheme from 1.5 days of $^{46}$K beam to GRIFFIN

- $\approx 200$ new gamma-ray transitions placed between 45 excited states
- States observed to within 815keV of the 7.7MeV $Q$-value.
- Branching ratios observed down to $10^{-3}$
- Weakest gamma ray observed has intensity of 0.0015% that of the $2_1^+ \rightarrow 0_1^+$ transition.
- Performing new shell model calculations and $\gamma-\gamma$ angular correlation analysis
Development of $\gamma - \gamma$ angular correlation analysis techniques with GRIFFIN using $^{66}\text{Ga}$ radioactive beam.

*M.Sc. Thesis, A. MacLean, Guelph 2016*
Define Polarization plane from $\gamma-\gamma$ coincidence detection. Then examine azimuthal scattering angle to determine electric or magnetic nature of the radiation.

$^{207}$Bi Example: Red=567keV E2  
Blue=1064keV M4+E5, $\delta_1=+0.03$ 

Dan Southall, TRIUMF research student, 2016
Measurement of decay half lives and properties are important for astrophysical r-process calculations

G. Lorusso et al. PRL 114 192501 (2015)
M. Mumpower et al., Prog.Part.Nucl.Phys. 86, 86 (2016)
New spectroscopic information in $^{128}$In from $^{128}$Cd beta decay

- PhD Nikita Bernier (UBC/ TRIUMF)

New: 23 new transitions, 15 new states

Formation of the ‘Rare-Earth Peak’

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

Graph showing isotopic abundance with mass number A and N=82, N=126, N=184.
S1625: “Decay spectroscopy of neutron-rich $^{160-166}$Eu isotopes with GRIFFIN” Spokespersons: I. Dillmann (TRIUMF), P.E. Garrett (Guelph)

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

*Diagram showing decay chains and solar system abundance.*

LaBr$_3$ Fast-Scintillator Array for Excited-State Lifetimes

- Eight LaBr$_3$(Ce) 2”x2” cylindrical crystal
- Source-detector distance=12.5 cm.
- GEANT4 simulated efficiency 1.4%@1.3MeV
- Hybrid analogue + digital electronics, excellent time resolution
- Effort led by Bruno Olaizola, University of Guelph

$^{146}$Cs $\beta$ decay: GRIFFIN + DESCANT + LaBr$_3$
August 2016

Preliminary

$T_{1/2}$ for $2^+$ state in $^{146}$Ba
GRIFFIN: 840(20) ps
Literature: 860(30)ps
The **Advanced Rare IsotopE Laboratory** will triple TRIUMF’s isotope beam capacity

- Uses state-of-the-art, made-in-Canada superconducting electron linear accelerator technology; targets are designed to allow medical isotopes to be extracted alongside the experimental program

- Represents ~$100 million investment by federal and provincial governments; supported by 19 university partners from across Canada

- Project to occur in two phases:
  - ARIEL-I completed in Fall 2014;
  - ARIEL-II funded by Canada Foundation of Innovation, funding now secured.

- Will provide more and new isotopes
TRIUMF-ISAC
Isotope Separator and ACcelerator

1 RIB delivery to experiments

500MeV p⁺ at 100μA on ISOL target

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

Yield Chart of Nuclides

15 Mar 2017

ISAC-I Low-Energy <60keV
ISAC-I Medium E  <1.5MeV/u
ISAC-II SC LINAC <10MeV/u

Ground state + decay, material science
Astrophysics
Nuclear reactions and structure
ARIEL Project:
- new electron linac driver for photo-fission
- new target stations and front end
- new proton beamline

E-linac and electron beamline
Sept. 2014
Rare-isotope beams will be produced by from proton and electron driver beams.
What we can do at ARIEL:

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

Triple the available beam time: more time for beam developments
Thank you!

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

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

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

Singly-charge RIB

Highly-charged RIB
ARIEL-1: e-linac completed and commissioned
- Target developments for $p$- and $\gamma$-fission targets with $^{238}\text{UC}_x$ (100kW)
- New target removal and exchange concept (internat. review)
- Test stand for e-hall
Photo-fission isotopes:

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

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

Modular target system, hermetically sealed units
FLUKA Production Map from 35 MeV Electrons

ARIEL Current Concept Design In-Target Production Yields [10 kW\(^{-1}\)·s\(^{-1}\)]

In-target production rates [10 kW\(^{-1}\)·s\(^{-1}\)];

- **from BeO:**
  - \(^{8}\)Li: \(5 \cdot 10^{10}\)

- **from UC\(_x\):**
  - \(^{78}\)Ni: \(1 \cdot 10^{5}\)
  - \(^{98}\)Kr: \(8 \cdot 10^{7}\)
  - \(^{100}\)Rb: \(1 \cdot 10^{8}\)
  - \(^{98}\)Sr: \(5 \cdot 10^{9}\)
  - \(^{132}\)Sn: \(5 \cdot 10^{8}\)
  - \(^{146}\)Xe: \(2 \cdot 10^{7}\)
  - \(^{144}\)Ba: \(5 \cdot 10^{9}\)
  - \(^{150}\)Cs: \(4 \cdot 10^{5}\)

500MeV Protons on UC\(_x\):

- \(^{78}\)Ni: \(2 \cdot 10^{6}\)
- \(^{98}\)Kr: \(1 \cdot 10^{8}\)
- \(^{100}\)Rb: \(9 \cdot 10^{7}\)
- \(^{98}\)Sr: \(1 \cdot 10^{10}\)
- \(^{132}\)Sn: \(5 \cdot 10^{9}\)
- \(^{146}\)Xe: \(1 \cdot 10^{7}\)
- \(^{144}\)Ba: \(2 \cdot 10^{10}\)
- \(^{150}\)Cs: \(5 \cdot 10^{5}\)

FLUKA: A. Gottberg (TRIUMF and results verified independently with GEANT4 (Marla Cervantes Smith, University of Victoria))
$^{144}\text{Ba}$ is doubly-magic for octupole deformation; $Z=56, N=88$.

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

10kW electrons: $5 \times 10^9$ with zero Nd