Nuclear Structure Experiments
RI beams@ ISAC/ARIEL

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Exploring Terra Incognita

- Discovering new features of nuclei at extremes of neutron/proton ratio
  - Understanding neutron-rich matter in the Universe
  - Understanding nuclear force and guidance for models
- Understanding $r$-process with structure of neutron-rich nuclei
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Stable nuclei

Nuclear Halo

- Changing face of the nucleus
- (N/Z>>1) Pure neutron surface
- rp-process in x-ray bursts
- Rare Isotopes (RI)
- Stable Isotopes

Number $Z$ of protons

Number $N$ of neutrons

Neutron star
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Nuclear Halo

- Changes of nuclear shells
- Pure neutron surface
- Stable nuclei
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- Pure neutron surface
- Stable nuclei

DTIUMF

ISAC / ARIEL

Number of neutrons

Nuclear Halo

(N/Z $>>$ 1)

Stable nuclei

Changing face of the nucleus

 neutron star

rp-process in x-ray bursts

Rare Isotopes (RI)

Stable Isotopes

Number Z of protons

Nuclear Halo

Changes of nuclear shells

(N/Z $>>$ 1)

Pure neutron surface

neutron star

Understanding neutron-rich matter in the Universe
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  - Understanding neutron-rich matter in the Universe
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- Changes of nuclear shells

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- Stable nuclei

- Rare Isotopes (RI)

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- Shape Coexistence

- Pure neutron surface

- Changing face of the nucleus
• Discovering new features of nuclei at extremes of neutron/proton ratio
  
  Understanding neutron-rich matter in the Universe
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• Understanding r-process with structure of neutron-rich nuclei
Stopped RI beam experiments

TITAN
Precision mass measurements

Collinear Laser Spectroscopy

GRIFFIN
Precision, high-efficiency β decay spectroscopy

Talk by J.D. Holt
$^{130}_{48}\text{Cd}$

Half Life: $r$-process
Half-Lives of Neutron-Rich $^{128-130}$Cd  

$T_{1/2}$ influences timescale of $r$-process

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

Nuclei near $N = 82$ are responsible for the $A \sim 130$ $r$-process abundance peak. These ‘waiting point’ nuclei are important in calculations of all astrophysical environments.
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Sensitivity of the $r$-process $\beta$ decay rates

130Cd beam

GRiffin : R. Dunlop et al., PRC 93, 062801(R) (2016).

Science Impact of TRIUMF data :
Resolves the discrepancy in half-life of $^{130}$Cd ($N = 82$). Creates new challenge for the calculated half-life of $^{131}$In.
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$^{130}$Cd beam

High precision $T_{1/2}$ measurements of neutron-rich nuclei needed to constrain nuclear models for $r$-process

Sensitivity of the $r$-process $\beta$ decay rates

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Resolves the discrepancy in half-life of $^{130}$Cd ($N = 82$).
Creates new challenge for the calculated half-life of $^{131}$In.
Laser spectroscopy of neutron-rich Rb isotopes probe details of the shape transition at $N=60$.

Two states observed (spin = 0 and spin =3)

Laser spectroscopy of neutron-rich Rb isotopes probe details of the shape transition at $N=60$.

Two states observed (spin $= 0$ and spin $=3$)

Charge Radii lie on same deformation line as $N = 60$, shows prolate deformation for BOTH states in $^{98}$Rb
Charge radius of $^{98}$Rb isomeric states

Laser spectroscopy of neutron-rich Rb isotopes probe details of the shape transition at $N=60$.

Two states observed (spin = 0 and spin =3)

$^{98}$Rb

Spin = 0  \(\text{(unknown level)}\)  Spin = 3  \(\text{Spin = 3}\)

Relative Frequency (MHz)


Isotope Shift

\[ \nu = \text{frequency of hyperfine structure} \]

Charge Radii lie on same deformation line as $N = 60$, shows prolate deformation for BOTH states in $^{98}$Rb

Unexpected feature and not yet explained by theory
Re-accelerated RI beam experiments

- E/A ~ 1.8 – 12 MeV
- High Quality
  (unique feature of TRIUMF re-accelerated beams)
- Emittance $0.3 \, \pi/\beta \, \text{mm mrad}$
- 1 $\, \pi \, \text{keV/u ns}$
Technical highlight: First high mass experiment at ISACII ($^{95}$Sr beam)
Shape co-existence in $^{94,96}$Sr : Transfer reaction

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Science highlight : • First observation of excited $0^+$ states in $^{94}$Sr

S. Cruz, Ph.D. thesis (UBC, 2017)
S. Bhattacharjee, S. Cruz et al, in preparation
Shape co-existence in $^{94,96}$Sr: Transfer reaction

Technical highlight: First high mass experiment at ISACII ($^{95}$Sr beam)

Science highlight:
- First observation of excited $0^+$ states in $^{94}$Sr
- $^{96}$Sr$_{gs}$ found to have small spherical shape component
- $^{96}$Sr($0_2^+, 0_3^+$) states higher spherical component coexist with deformed component

Not explained yet by shell model

$|0^+_2\rangle = a|0_{sph}^+\rangle + \sqrt{1-a^2}|0_{def}^+\rangle$

S. Cruz, Ph.D. thesis (UBC, 2017)
S. Bhattacharjee, S. Cruz et al, in preparation
$^{11}_{3}\text{Li}$

Halo driven new excitation

Neutron Halo

Neutron Number

Proton Number
Search for Soft Dipole Resonance in $^{11}$Li halo

Science highlight: Isoscalar soft dipole state observed $\Rightarrow$ strong correlation of surface neutrons

R. Kanungo, A. Sanetullaev, J. Tanaka et al.
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Confirmed evidence seen @ TRIUMF after two decades since first postulated

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$^{11}$Li signature beam of TRIUMF

$^{11}$Li target

Solid $D_2$ target

Dipole

Soft Dipole Resonance

Giant Dipole Resonance

\[ E/A = 5 \text{ MeV} \]
Search for Soft Dipole Resonance in $^{11}$Li halo

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Soft dipole resonances can enhance neutron capture rates ($r$-process). ARIEL will help explore them in heavier nuclei.
New: Electromagnetic Mass Analyzer (EMMA)

• Detection of heavy recoil nuclei in reactions
• Separation of beam from reaction recoils

Mass/Charge Spectrum from 84 MeV $^{23}$Na on natCu
Beam suppression $>10^{12}$

Four approved experiments:
• Isospin symmetry for states in $^{21}$Ne and $^{21}$Na
• Capture cross sections for s- and p-processes
• ($p,\alpha$) reaction cross section for hot CNO cycle breakout

Program to start in Spring 2019 following installation of TIGRESS around EMMA target
Future Perspectives @ ARIEL

Enable a multitude of high-impact nuclear structure measurements at TRIUMF

• What are the characteristics of nuclei at N/Z >> 1?
  Changes in nuclear shell structure and evolution of shape coexistence (masses, transfer reactions, transition rates, charge radii)
  New signatures in pairing correlation (two-nucleon transfer reactions)
  New excitation modes (soft dipole) (inelastic scattering)

• What is the universal prescription of the nuclear force and nuclear model?
  Constraining ab initio theory (elastic scattering, inelastic scattering, excited states, masses, magnetic and quadrupole moments)

• Nuclear structure for understanding the origin of heavy elements in nature
  Constraining neutron capture cross sections for r-process (transfer reactions)
  Constraining nuclear models from precise measurements of masses and beta decay rates (masses, half-lives)

CANREB – ARIEL will enable experiments with high-mass re-accelerated beams
Acknowledgements


Thank you for your attention
Backup Slides
Search for Soft Dipole Resonance in $^{11}\text{Li}$ halo

$^{11}\text{Li}(p,p')$


- Shell model (SFO-tls): tensor in $p$-$sd$ shell part explaining the $\pi+\rho$ meson exchange potential
- Coupled Cluster: with chiral NN force. Need to include effect of continuum.
- Three-body models: Resonances very closely spaced.
Soft Dipole Resonance and neutron capture rate

S. Goriely, PLB, ’98
Half-Lives of Neutron-Rich $^{128-130}$Cd

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50 $^{132}$Sn  
49 $^{131}$In  
48 $^{130}$Cd  
47 $^{129}$Ag  
46 $^{128}$Pd  
45 $^{127}$Rh  
N=82

G. Lorusso et al. PRL 114 192501 (2015)  
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