Radioactive beams from e-beam driven photofission

eRIBs’07
Workshop
Jim Beene
ORNL
October 10, 2007
Outline

• HRIBF & some highlights of the n-rich research program
  – Motivation for an e-beam driver upgrade

• Photofission for RIB production: some advantages, some disadvantages

• Comments on properties and capabilities of a e-beam driven facility
HRIBF Post-accelerated Beams

175 RIB species available
(+26 more unaccelerated)
32 proton-rich species
143 neutron-rich species

Beam list increased by ~50% since 2003
The first transfer measurements on N=82 nuclei on / near r-process path

- yields, angular distributions of low-lying states measured
- first observation of $p_{1/2}$ state in $^{133}$Sn
- three other states in $^{133}$Sn measured, calibrated with $^{130}$Te(d,p)
- evidence for numerous states in $^{131}$Sn never seen before
- evidence that the $f_{5/2}$ level in $^{135}$Te is at a significantly higher energy

$^{130}$Sn(d,p)$^{131}$Sn - R. Kozub et al.
$^{132}$Sn(d,p)$^{133}$Sn - K.L. Jones et al.
$^{134}$Te(d,p)$^{135}$Te - S.D. Pain et al.

K. Jones
Decay spectroscopy of exotic nuclei

β-decay studies around $^{78}$Ni with postaccelerated (3 MeV/u) pure neutron-rich RIBs

Winger et al.

- Absolute beta-delayed neutron branching ratios for $^{76-79}$Cu and $^{83-84}$Ga
- Identification of new excited states in $^{77}$Zn, $^{78}$Zn, $^{82}$Ge, $^{83}$Ge, and $^{84}$Ge
- Systematics of single particle levels (e.g. neutron $s_{1/2}$) near doubly magic $^{78}$Ni

Range out unwanted high-Z contamination with high pressure & tape transport

Discovery of superallowed α-decay

$\delta^2(^{105}$Te)/$\delta^2(^{213}$Po) $\sim 3$

- Enhanced due to the same proton and neutron shell structure
- rp-process termination
- En route to $^{104}$Te $\rightarrow ^{100}$Sn

S. Liddick et al., PRL 97, 2006, 082501

$^{109}$Xe $\rightarrow$ $^{105}$Te $\rightarrow$ $^{101}$Sn

$^{105}$Te $^{53}$

$^{101}$Sn $^{51}$
Pioneering studies with neutron-rich radioactive beams of heavy nuclei

**Fusion & Fission**
- Probing the influence of neutron excess on fusion at and below the Coulomb barrier
- Large sub-barrier fusion enhancement has been observed
- Inelastic excitation and neutron transfer play an important role in the observed fusion enhancement
- Important for superheavy element synthesis
- ERs made with $^{132,134}$Sn cannot be made with stable Sn

**Coulex**
- Probing the evolution of collective motion in neutron-rich nuclei
- Increasingly larger contributions of neutrons to $B(E2)$ values above $^{132}$Sn
- Recoil-in-Vacuum technique used to measure the g-factor for the first $2^+$ state in $^{132}$Te:

\[ \text{g-factor} \]

Liang et al., PRL 91, 15271 (2003); PRC 75, 054607 (2007)

Coulex of $n$-rich nuclei around $A=80$ at HRIBF

Particle-$\gamma$ coincidence spectra

RIB $A=78 + ^{12}\text{C} @ 174.5$ MeV

$I = 1.4 \times 10^6$ pps

$57.1\%$ $^{78}\text{Ge}$, $28.1\%$ $^{78}\text{Se}$, $9.9\%$ $^{78}\text{As}$, $4.9\%$ $^{78}\text{Ga}$

RIB $A=80 + ^{12}\text{C} @ 179$ MeV

$I = 1.4 \times 10^5$ pps

$93.5\%$ $^{80}\text{Ge}$, $2.2\%$ $^{80}\text{Se}$

RIB $A=82 + ^{48}\text{Ti} @ 220$ MeV

$I = 5.5 \times 10^4$ pps

$19.2\%$ $^{82}\text{Ge}$, $1.8\%$ $^{82}\text{As}$, $79\%$ $^{82}\text{Se}$

E. Padilla-Rodal et al.
PRL94, 122501 (2005)

Purified using $^A\text{GeS}^+$

$B(E2;0^+ \rightarrow 2^+) [e^2b^2]$

This work, SIBs

This work, RIBs

Adopted value, S. Raman et al.

Shell Model calculation

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Coulomb Excitation of $^{84}$Se (N=50)

$E_{\text{beam}} = 193.2$ MeV; nat Al target
Beam composition: ~ 44% $^{84}$Se, ~ 56% $^{84}$Br, ~ 1% $^{84}$Rb
I(A=84) ~ 2-3 x 10^4 pps

FIG. 3. $E(2^+_1)$ and $B(E2)$ values for $N = 50$ isotones. The dashed and dotted lines correspond to SM calculations.
RISAC Science Drivers
& the electron driver

- **Nuclear Structure**
  - Probing the disappearance of shells
    - Spectroscopy & reactions in $^{132}\text{Sn}$, $^{78}\text{Ni}$ regions
  - Evolution of collective motion
    - We can probe $^{112}\text{Zr}$ and $^{96}\text{Kr}$ regions (not $^{156}\text{Ba}$)
  - Neutron Skins
    - Structure/reaction studies of the most n-rich species
  - SHE
    - Reactions with $^{132}\text{Sn}$ ($\sim 10^9$) and vicinity
    - For $Z=112$, $N=184$, reaction mech. Studies with $^{92,94}\text{Sr}$ ($10^6, 10^7$)

- **Nuclear Astrophysics**
  - Decay spectroscopy ($\beta n$, $\tau$)

- **Stockpile Stewardship**
  - Surrogate reactions (n transfer, etc.)
HRIBF view of e-beam driver upgrade

- The discussion of a photo-fission driver that follows was developed based on specific considerations relevant to HRIBF

- We have particular boundary conditions:
  - A turn-key simple-to-maintain accelerator
  - A concept that “guarantees” a minimum level of performance without need of major targetry breakthroughs.
  - A capability dedicated to extending our reach toward very n-rich nuclei in a timely manner
HRIBF as a two driver facility

• We are developing a proposal for a turn-key electron accelerator (e-machine), capable of providing CW ~ 100kW beams with energies at or above 25 MeV.

• This accelerator would be dedicated to producing neutron-rich species by photofission of actinide targets.

• Such an accelerator is by far the most cost effective means to achieve in-target fission rates in the mid 10¹³/s scale.

• A comparable upgrade to our p-rich capability would be far more expensive

• Target development to support operation at >10¹³f/s (~50kW )is well in hand. Thus we are confident we can reach fission rates about 20 times larger than current HRIBF capability.

• The increase in fission rate is not, however a good comparative metric.
  – Photofission is a “colder” process than proton induced fission.
  – It results in lower actinide excitation, and less neutron evaporation from both the excited actinide system and the fragments.
  – Consequently production of very neutron-rich species can be enhanced by a substantial factor compared to 50 MeV proton induced fission, at the same fission rate.
$^{238}\text{U}$ photo-fission is dominated by the GDR
$^{238}$U photo-fission is dominated by the GDR

$<E> = 12.9$

$\nu_n = 3.5$
\(^{238}\text{U}\) photo-fission is dominated by the GDR

\[
\begin{align*}
\langle E \rangle &= 12.98 \quad (50) \\
\nu_n &= 3.5 \\
\langle E \rangle &= 12.81 \quad (25) \\
\nu_n &= 3.4
\end{align*}
\]
$^{238}\text{U}$ photo-fission is dominated by the GDR

$\langle E \rangle = 12.98$  \quad $\nu_n = 3.5$ \hspace{1cm} (50),

$\langle E \rangle = 9.4$  \quad $\nu_n = 3.0$ \hspace{1cm} (12)
But photo-fission is not the dominant GDR decay channel

- $(\gamma,n)$ and $(\gamma,2n)$ account for $\sim 2/3$ of GDR cross section
- Substantial $^{236,237}\text{U}$ production is inevitable

Data from Livermore and Saclay groups
Photofission yields

- $10^{13}$ f/s “easily” achieved
- About 20x current HRIBF
- But real gain >> 20x

$^{238}\text{U}(\gamma,f)$ systematics from Tsukada
$(\gamma,F)$ from ORNL systematics + Jyvaskyla model
A sample comparison with data: Sn isotopes
Neutron multiplicities associated with fission are important figures of merit for our purposes

- **Proton induced fission at HRIBF energies**
  - $E_p=50\text{ MeV} \rightarrow \nu_n=8.5$
  - $E_p=500\text{ MeV} \rightarrow \nu_n\sim13$

- **Electron induced photofission:**
  - $E_e=25\text{ MeV} \rightarrow \nu_n=3.3$
  - $E_e=50\text{ MeV} \rightarrow \nu_n=3.4$

- **Neutron-induced fission is very similar in many ways to photofission.** $^{238}\text{U}(n,F) \oplus \sim15\text{ MeV}$ has final state properties very similar to $E_0=25-50\text{ MeV}$ photofission.
RIB production by photofission

\[ \frac{10^{13} \text{ ph-f/s}}{10 \mu\text{A} 40 \text{ MeV p}} \]

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Conservative target design for performance determination

\[ \rho = 3 \text{ g/cm}^3 \]
\[ d = 3 \text{ cm} \ (0.3 \ R_M) \]
\[ t = 30 \text{g/cm}^2 \ 5X_0 \ (10 \text{cm}) \]
\[ M = 212 \text{ g} \]

\[ \rho = 6 \text{ g/cm}^3 \]
\[ d = 3 \text{ cm} \ (0.6 \ R_M) \]
\[ t = 30 \text{g/cm}^2 \ 5X_0 \ (5 \text{cm}) \]
\[ M = 212 \text{ g} \]

\[ X_0 = 6 \text{ g/cm}^2 \ (U) \]
Photofission target issues/ limitations

Direct bombardment

- e-beam directly incident on targets
  - If $10^{13}$ goal is to be met, beam energies less than ~80 MeV may give problems using current target technology without further testing and or development.
Fission rate and power in target

Effect of a converter

What it takes to make $10^{13}$ fissions/s
Photofission target issues
Converter + target

 Beam energy (MeV)  
- 25  
- 50  
- 100  
- 200  

Power in target (kW): $10^3$ fis. s$^{-1}$

Converter thickness (rad lengths, W)

Yield (fissions/cm$^3$) $\times 10^4$

No converter
Beam energy MeV  
- 25  
- 50  
- 100  
- 200  

3 cm diameter
3 g/cm$^3$
What about even lower e-energy?

- For $E_e=12$ MeV, beam power $> 200$ kW is required to reach $10^{13}$ f/s
What about even lower e-energy?

- For $E_e \sim 12$ MeV, power deposited in target is $\sim 5x$ greater than for $E_e = 25$ or greater to reach $10^{13}$ f/s.
- Lower $E^*$ may enhance n-rich yield.

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An example of a somewhat more aggressive design

\[ \rho = 6 \text{ g/cm}^3 \]
\[ t = 30 \text{g/cm}^2 \ (5X_0) \]
\[ M = 495 \text{ g} \]

2.3 x UC\(_x\) front surface area compared to 3 cm dia. Cylinder

Similar power required to reach \(10^{13}\) f/s (52kW @ 25 MeV)
Power Density in Targets

HRIBF
15 μA
50 MeV p

320 W/g

50 MeV p 0.75 kW (1.4x2 cm 2 g/cc)

~60 kW
50 MeV e

200 W/g

50 MeV e 55 kW (5x3 cm 6 g/cc)

$10^{13}$ fissions/s

15 MeV p

Power density (W/g)

- 4.00E+02-5.00E+02
- 3.00E+02-4.00E+02
- 2.00E+02-3.00E+02
- 1.00E+02-2.00E+02
- 0.00E+00-1.00E+02

Power Density W/g

- 2.00E+02-2.50E+02
- 1.50E+02-2.00E+02
- 1.00E+02-1.50E+02
- 5.00E+01-1.00E+02
- 0.00E+00-5.00E+01
Power Density in Targets

50 MeV e- 48 kW (5x5 cm 6g/cc)

10^{13} \text{fiss./s}

80 W/g
Conclusions I: RIB production

- $10^{13}$ f/s can be achieved with an ~50 kW facility
  - Requires only modest sized targets to achieve initial goals
    - 3 cm x 5 cm (212 g)
    - <10 kW deposited in target
    - 25 MeV e beam can be used with converter
      - Additional technologies can be considered
  
- Substantially larger yields can be achieved with larger targets and higher beam powers
  - 500g to 1kg & 100-150 kW
  - What is release time?

- Even with thick converters, cannot isolate production target from beam power and still produce fission at high rates

- Pulsed e-beam can aggravate thermal and mechanical stress issues in target.
Conclusions II: Shielding

- Thick target bremsstrahlung:
  - $\theta_{1/2} \sim 100/E_0$ degrees
  - Forward angle $\gamma$ dose rate
    - $D \sim 300 E_0 \text{ Gy h}^{-1} \text{ (kW m}^{-2}\text{)}^{-1}$
    - $D \sim 1.5 \times 10^7 \text{ Gy h}^{-1}$ at 1 m for 50 MeV, 1MW e beam
      - 6m concrete or ~1m Fe
  - 90° $\gamma$ dose rate
    - $D \sim 70 \text{ (Gy h}^{-1}\text{)(kW m}^{-2}\text{)}^{-1}$
    - $D \sim 7 \times 10^4 \text{ Gy h}^{-1}$ at 1m for 1MW e beam ($E_0 > 20 \text{ MeV}$)

Photo-fission yield

In target

HRIBF UC target production rates
(produced via photofission of U-238 at $10^{13}$ fissions/second)
Photo-fission yield

From ion source

HRIBF beams directly from the ion source - unaccelerated beams
(produced via photofission of U-238 at $10^{13}$ fissions/second)
Photo-fission yield

Post-accelerated

HRIBF accelerated beam-on-target intensities
(produced via photofission of U-238 at $10^{13}$ fissions/second)
Science highlights with e-driver upgrade

→ Will test the evolution of nuclear structure to the extremes of isospin
→ Will improve our understanding of the origins of the heavy elements

Evolution of single-particle structure
Transfer reactions at $^{132}$Sn & beyond

Collective properties in extended neutron radii
Coulomb excitation near $^{96}$Kr

Reaction mechanisms for the formation of superheavy nuclei

Decay properties of nuclei at the limits
Crucial for understanding the formation of elements from iron to uranium
More to Come

• Alan Tatum will discuss
  – Discuss current status of HRIBF upgrade program
  – Discuss options for actual implementation of an e-beam driven facility that meets our requirements
  – Show preliminary facility layouts

• Dan Stracener will discuss target issues (the key to overcoming performance limitations, and going well beyond $10^{13}$ fissions second)
Conclusion

- Science with neutron-rich fission fragment beams is the keystone of our research program and will continue to be.
- An electron-beam based facility can produce intense beams in a cost-effective way.
- Such a facility would be competitive world-wide for neutron-rich beams until FRIB-scale facilities are available.
  - $10^{13}$ photo-fissions/second is a reasonable baseline to work from.
- Cost containment is critical – cost-effectiveness is a major part of the argument.
- There is a relatively short window during which such a facility is relevant.
Extra material
Decay studies pushing the frontier of n-rich nuclei

**Examples with eMachine**

<table>
<thead>
<tr>
<th>Ion</th>
<th>200 keV (ions/s)</th>
<th>Tandem (ions/s)</th>
<th>$t_{1/2}$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{78}\text{Ni}$</td>
<td>0.3</td>
<td>0.001</td>
<td>0.11</td>
</tr>
<tr>
<td>$^{80}\text{Cu}$</td>
<td>1000</td>
<td>4</td>
<td>?</td>
</tr>
<tr>
<td>$^{81}\text{Cu}$</td>
<td>7</td>
<td>0.3</td>
<td>?</td>
</tr>
<tr>
<td>$^{82}\text{Zn}$</td>
<td>5000</td>
<td>0</td>
<td>?</td>
</tr>
<tr>
<td>$^{94}\text{Br}$</td>
<td>$1 \times 10^4$</td>
<td>100</td>
<td>0.07</td>
</tr>
<tr>
<td>$^{96}\text{Br}$</td>
<td>56</td>
<td>4</td>
<td>?</td>
</tr>
<tr>
<td>$^{137}\text{Sn}$</td>
<td>1800</td>
<td>45</td>
<td>0.19</td>
</tr>
<tr>
<td>$^{138}\text{Sn}$</td>
<td>89</td>
<td>2</td>
<td>?</td>
</tr>
<tr>
<td>$^{137}\text{Sb}$</td>
<td>$9 \times 10^5$</td>
<td>$2 \times 10^4$</td>
<td>?</td>
</tr>
<tr>
<td>$^{140}\text{Sb}$</td>
<td>980</td>
<td>17</td>
<td>?</td>
</tr>
<tr>
<td>$^{149}\text{Cs}$</td>
<td>$2 \times 10^4$</td>
<td>4</td>
<td>?</td>
</tr>
</tbody>
</table>

$t_{1/2}$ & $\beta n$ rates for many $r$ process nuclei are accessible

Energy levels test evolving nuclear structure
The evolution of single-particle levels and shapes in very neutron-rich nuclei beyond the N=50 shell closure

β-decay experiments with postaccelerated (3 MeV/u) pure neutron-rich RIBs, Oct-Nov 2006

<table>
<thead>
<tr>
<th>beam</th>
<th>$T_{1/2}$ (s)</th>
<th>main results</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}$Cu</td>
<td>0.65</td>
<td>$\beta_n$-branching ratio $I_{\beta_n}$</td>
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<tr>
<td>$^{77}$Cu</td>
<td>0.46</td>
<td>$I_{\beta_n}$, $\nu$-levels in N=47 $^{77}$Zn</td>
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<tr>
<td>$^{78}$Cu</td>
<td>0.35</td>
<td>$I_{\beta_n}$, $I_\pi$ of $^{78}$Cu$_{49}$ revised</td>
</tr>
<tr>
<td>$^{79}$Cu</td>
<td>0.19</td>
<td>$\beta_n\gamma$ decay observed first time</td>
</tr>
<tr>
<td>$^{83}$Ga</td>
<td>0.30</td>
<td>$\beta_n\gamma, \beta\gamma$, $\nu s_{1/2}$ in N=51 $^{83}$Ge</td>
</tr>
<tr>
<td>$^{84}$Ga</td>
<td>0.08</td>
<td>$2^+$ in N=52 $^{84}$Ge, $\nu s_{1/2}$ in $^{83}$Ge</td>
</tr>
<tr>
<td>$^{85}$Ga</td>
<td>~0.07</td>
<td>rate of 0.1pps…</td>
</tr>
</tbody>
</table>

Jeff Winger et al.

eRIBs’07
The evolution of single-particle levels and shapes in very neutron-rich nuclei beyond the N=50 shell closure

Nov'06: experiment with 2 pps of 3 MeV/u $^{84}$Ga

$^{84}$Ga $\rightarrow$ $^{84}$Ge* $\rightarrow$ $^{83}$Ge* ($\nu_{s_{1/2}}$) $\rightarrow$ $^{83}$Ge ($\nu_{d_{5/2}}$)

$^{84}$Ga $\rightarrow$ $^{84}$Ge* (2+) $\rightarrow$ $^{84}$Ge (0+)

$\beta$ $n$ $\gamma$

$\beta$-gated $\gamma$-spectrum (0.5 keV/ch)

N=51 $^{83}$Ge

248 keV

N=52 $^{84}$Ge

625 keV

$\beta$-gated $\gamma$-spectrum (0.5 keV/ch)
Transfer reactions: shell structure of n-rich nuclei

Single-particle states around closed shells provide a fundamental shell model test

Example: (d,n)-like reactions → neutron s.p. levels

Recoils detected in coincidence

protons detected in Si-array

\[ ^{132}\text{Sn}(d,p)^{133}\text{Sn} @ \text{HRIBF} \]

\[ \text{Jones et al.} \quad 6 \times 10^4 \text{ ions/s} \]

Single-particle transfer near \(^{78}\text{Ni}\) and \(^{132}\text{Sn}\)

Reactions of interest

\((d,p)\)
\((^9\text{Be}, ^8\text{Be})\)
\((^3\text{He}, d)\)
\((^3\text{He}, \alpha)\)
\((^7\text{Li}, ^8\text{Be})\)

<table>
<thead>
<tr>
<th>Ion</th>
<th>Intensity (ions/s)</th>
<th>(t_{1/2}) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{84}\text{Ge})</td>
<td>(3 \times 10^5)</td>
<td>0.9</td>
</tr>
<tr>
<td>(^{88}\text{Se})</td>
<td>(3 \times 10^4)</td>
<td>1.5</td>
</tr>
<tr>
<td>(^{96}\text{Sr})</td>
<td>(7 \times 10^4)</td>
<td>1.1</td>
</tr>
<tr>
<td>(^{98}\text{Sr})</td>
<td>(1 \times 10^4)</td>
<td>0.65</td>
</tr>
<tr>
<td>(^{134}\text{Sn})</td>
<td>(3 \times 10^6)</td>
<td>1.0</td>
</tr>
<tr>
<td>(^{138}\text{Te})</td>
<td>(5 \times 10^6)</td>
<td>1.4</td>
</tr>
<tr>
<td>(^{140}\text{Te})</td>
<td>(2 \times 10^4)</td>
<td>?</td>
</tr>
</tbody>
</table>

eRIBs’07

\(E_p\) (channels) \(\rightarrow\) \(E_x\)
$^{13}\text{C}(^{134}\text{Te},^{12}\text{C})^{135}\text{Te}$ neutron transfer

Particle-gamma angular correlations

$^{133}\text{Sn}$ $^{135}\text{Te}$ $^{137}\text{Xe}$ $^{139}\text{Ba}$ $^{141}\text{Ce}$ $^{143}\text{Nd}$ $^{145}\text{Sn}$

$E_\gamma$ (keV)

2109 keV

929

1180

657

1279

134 Te 2+

$^{133}\text{Te}$

424

$p_{1/2} \rightarrow p_{3/2}$

$p_{3/2}$

$\phi_{\gamma} - \phi_\phi$ [degrees]
Coulomb excitation in n-rich systems

Probes the evolution of collective motion in loosely-bound, neutron-rich nuclei

n-rich beams
C, Ti, Zr

target

Charged-particle
⊗
Gamma array

With eMachine: neutron-rich nuclei from N=50 to N=82 (and beyond) are accessible

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<tr>
<td>$^{98}$Sr</td>
<td>$1 \times 10^4$</td>
<td>0.65</td>
</tr>
<tr>
<td>$^{136}$Sn</td>
<td>700</td>
<td>0.25</td>
</tr>
<tr>
<td>$^{138}$Te</td>
<td>$5 \times 10^6$</td>
<td>1.4</td>
</tr>
<tr>
<td>$^{140}$Te</td>
<td>$2 \times 10^4$</td>
<td>?</td>
</tr>
</tbody>
</table>
Heavy ion fusion reactions

Probes the influence of neutron excess on fusion at and below the Coulomb barrier → important for superheavy element synthesis

More n-rich projectiles

Further below barrier $^{134}\text{Sn}$ below 10 mb

Transfer reaction studies on the same system will help to understand reaction mechanism

Liang et al.
Unattenuated angular correlations: Theory & experiment

$^{130}\text{Te SIB}$

Hyball Ring 2

$W(\Delta \phi)$

$\theta_\gamma = 155^\circ$

$\theta_\gamma = 132^\circ$

$\theta_\gamma = 90^\circ$

$^{130}\text{Te beam}$

$^{12}\text{C recoil}$

scattered $^{130}\text{Te}$ stopped in Cu
Magnetic moment: RIV attenuated angular correlations
# Neutron transfer reactions

### Accessible at HRIBF

<table>
<thead>
<tr>
<th>Element</th>
<th>Accessible at HRIBF</th>
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<td>Ce</td>
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### Accessible with e-machine

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Coulex (1-step)

Accessible at HRIBF

Accessible w e-machine

Ce  La  Ba  Cs  Xe  I  Te  Sb  Sn  In  Cd  Ag  Pd

66  70  74  78  82  86
Multi-step Coulex

Accessible at HRIBF

Accessible w e-mach

Ce  La  Ba  Cs  Xe  I  Te  Sb  Sn  In  Cd  Ag  Pd

66  70  74  78  82  86
g-factor measurements

Accessible at HRIBF
Accessible w/e-mach

Ce  La  Ba  Cs  Xe  I  Te  Sb  Sn  In  Cd  Ag  Pd

66  70  74  78  82  86