Heavy Element Synthesis
Reactions

W. Loveland
Oregon State University
The role of ATLAS in helping us understand heavy element synthesis reactions and heavy element properties

- Hot ($E^* = 35-60$ MeV) and Cold ($E^* = 15$ MeV) fusion reactions
- Multi-nucleon transfer reactions
- Fission
- Atomic physics and chemistry of the heaviest elements
- Structure of the heaviest nuclei
The challenge of studying the heaviest elements at ATLAS

- ATLAS beam time is oversubscribed
- Low cross section studies
  - High luminosity
  - ATLAS has increased beam currents
  - Need advances in targetry to utilize high beam currents.
  - Example: 1 pb cross section, 10 pμA
    > 40 events/week
Production of Heavy Elements in Complete Fusion Reactions

\[ \sigma_{EVR}(E_{\text{c.m.}}) = \sum_{J=0}^{J_{\text{max}}} \sigma_{\text{CN}}(E_{\text{c.m.}}, J) W_{\text{sur}}(E_{\text{c.m.}}, J), \]

where

\[ \sigma_{\text{CN}}(E_{\text{c.m.}}) = \sum_{J=0}^{J_{\text{max}}} \sigma_{\text{capture}}(E_{\text{c.m.}}, J) P_{\text{CN}}(E_{\text{c.m.}}, J), \]

- We need to know three spin-dependent quantities: (a) the capture cross section, (b) the fusion probability and (c) the survival probability, and their isospin dependence
Prediction of cold fusion cross sections
Despite correctly predicting $\sigma_{EVR}$ correctly, the values of $P_{CN}$ (and $W_{sur}$) differ significantly.
What experiments will be best done at ATLAS?

• Fusion probability (least known factor)

Techniques

Fission fragment angular distributions (determine quasifission component (Back))

$^{266}$Rf, $^{270}$Sg, $^{274}$Hs, $^{278}$Ds, $^{273-286}$Cn

Ghosal/ANU expt.
Form the same CN several different ways with at least one reaction having $P_{CN}=1$. Measure $\sigma_{EVR}$
What experiments will be best done at ATLAS?

Survival probabilities

• Focus on hot fusion reactions where $E^* = 35-60$ MeV and “shell effects” have “washed out” ($B_f \sim 0-1$ MeV)
• Example $^{274}$Hs ($E^* = 63$ MeV) \textit{(PRL 112, 152702 (2014))}
• $\Gamma_n/\Gamma_{total} = 0.89$
• Effect of nuclear viscosity (Kramers)
• One must consider macroscopic and microscopic effects
Why Hot Fusion Works

What experiments will be best done at ATLAS?

- Why best?
- National user facility for stable beams
- Wide range of projectiles and energies and ability to handle heavy element targets.
- New facilities (AGFA)
- Ability to mount “non-standard” experiments ($\Gamma_n/\Gamma_f$, fission neutron multiplicity)
Multi-nucleon Transfer

• Sparked by the work of Zagrebaev and Greiner, there is renewed interest in making new n-rich heavy nuclei by multi-nucleon transfer reactions.
$^{208}$Pb region

$^{136}$Xe + $^{208}$Pb, $E_{\text{cm}}$ = 450 MeV

Reaction mechanisms
Nuclear spectroscopy
r-process waiting point
Gammasphere expts.
Radiochemistry expts.
New actinide nuclei

$^{238}U + ^{248}Cm, E_{c.m.} = 780$ MeV
FUTURE: Multinucleon transfer in the heavy element region

radioactive ion-beam

$^{144}\text{Xe} + ^{248}\text{Cm}$, multinucleon-transfer products

$>10\,\mu\text{b}$

Calculations from Giovanni Pollarolo, Torino: Physics of multi-nucleon transfer reactions, EURISOL Town Meet. 2 – Abano Jan. 2002

SPIRAL 2 expects $^{144}\text{Xe}$ to be $5\times10^7$/s ($5.7\times10^5$-day1); FRIB 5.63; CARIBU 2.33
Summary

- There is an exciting array of forefront physics with heavy elements at ATLAS.
- I have only touched one aspect, nuclear reactions.
- Nuclear structure studies with the heavy elements have been and will continue to be important.