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

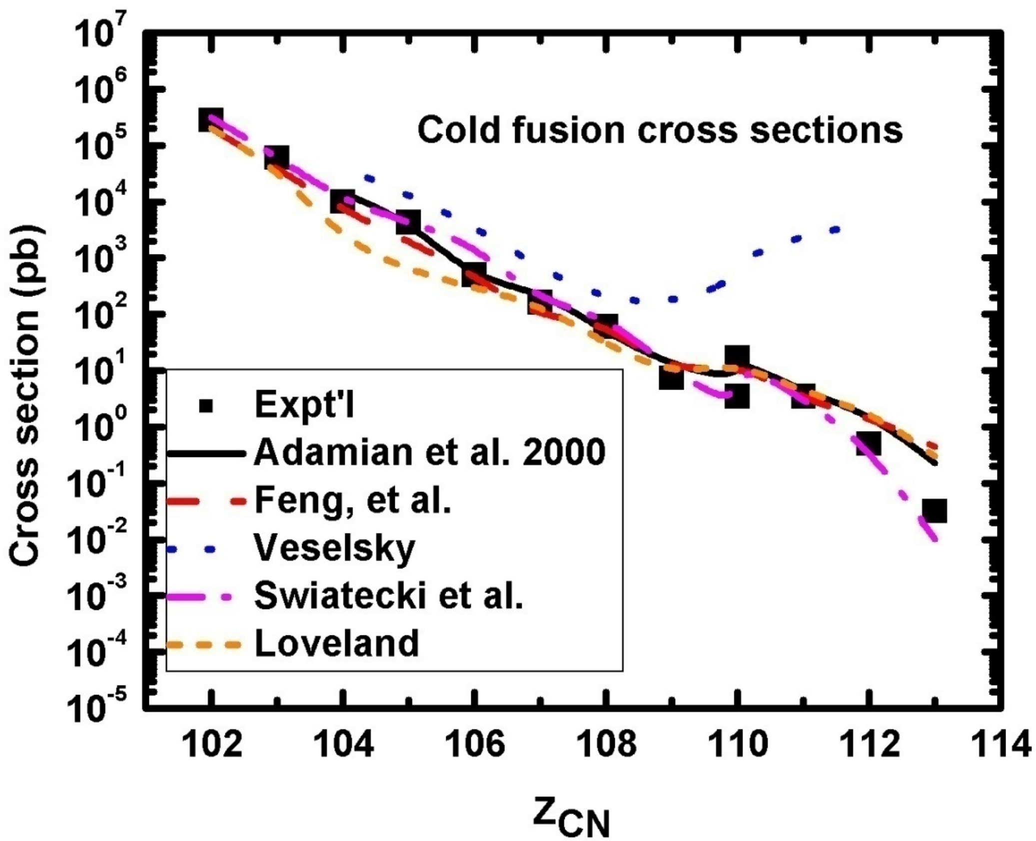
$$\sigma_{\mathrm{EVR}}(E_{\mathrm{c.m.}}) = \sum_{J=0}^{J_{\max}} \sigma_{\mathrm{CN}}(E_{\mathrm{c.m.}}, J) W_{\mathrm{sur}}(E_{\mathrm{c.m.}}, J),$$

where

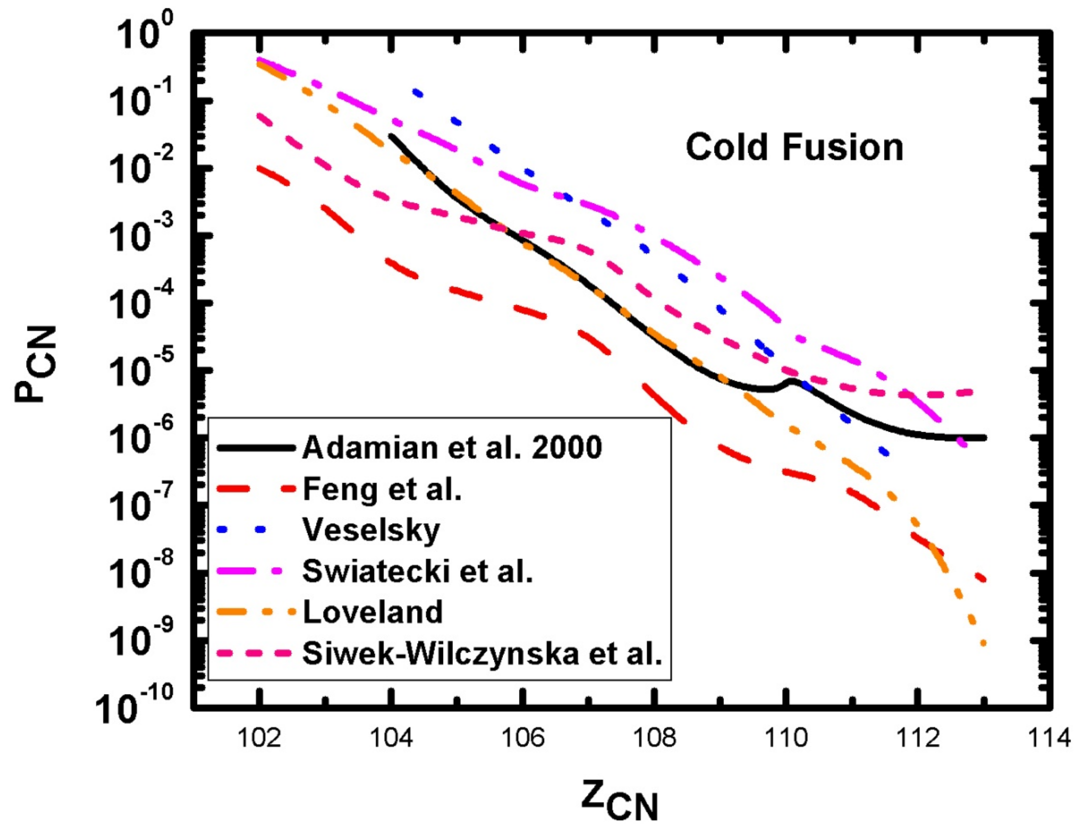
$$\sigma_{\mathrm{CN}}(E_{\mathrm{c.m.}}) = \sum_{J=0}^{J_{\max}} \sigma_{\mathrm{capture}}(E_{\mathrm{c.m.}}, J) P_{\mathrm{CN}}(E_{\mathrm{c.m.}}, J),$$

- 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

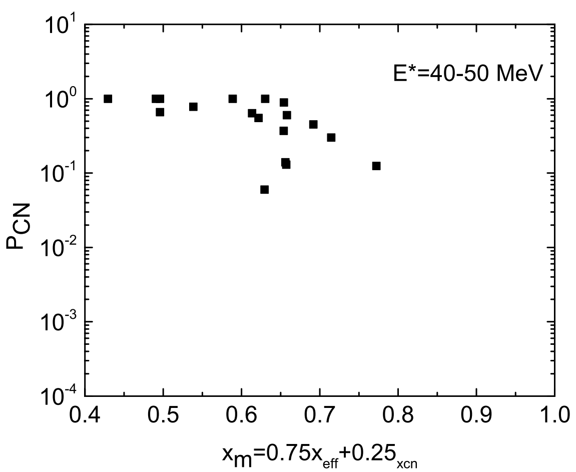


Despite correctly predicting σ_{EVR} correctly, the values of P_{CN} (and W_{sur})differ significantly



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, $^{273-286}Cn$

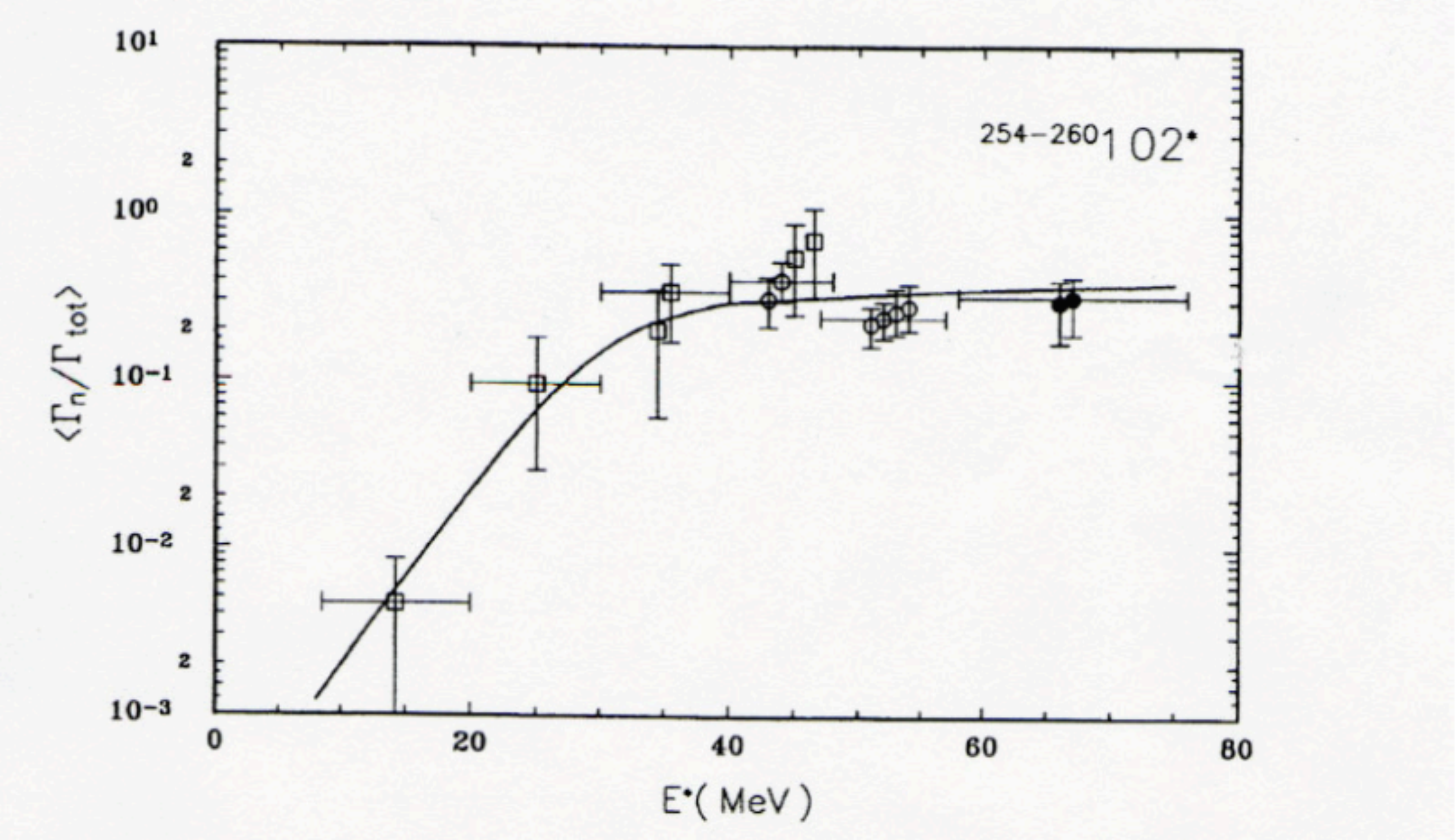
Ghoshal/ANU expt.
Form the same CN several different ways with at least one reaction having $P_{CN}=1$. Measure σ_{EVR}

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~0-1 MeV)
- Example ^{274}Hs (E^*=63 MeV) (PRL 112, 152702 (2014))
- Γ_n/Γ_{total} =0.89
- Effect of nuclear viscosity (Kramers)
- One must consider macroscopic and microscopic effects

Why Hot Fusion Works



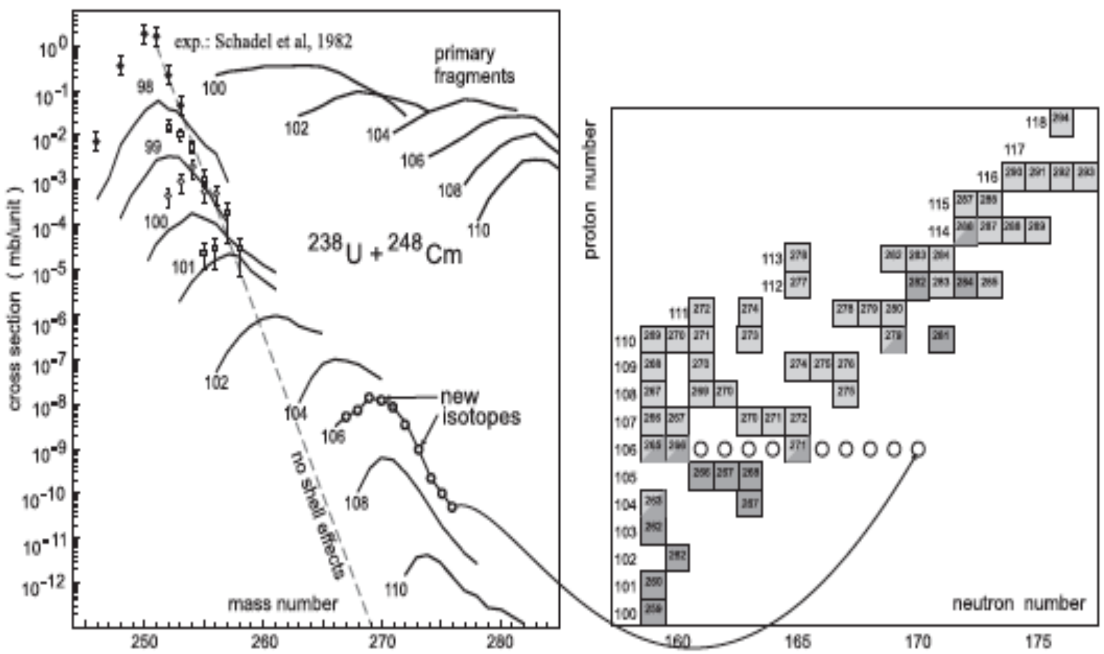
Andreyev A N *et al* 1994 *Heavy-Ion Fusion: Exploring the Variety of Nuclear Properties* (Singapore: World Scientific) p 260

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 (Γ_n/Γ_f, fission neutron multiplicity)

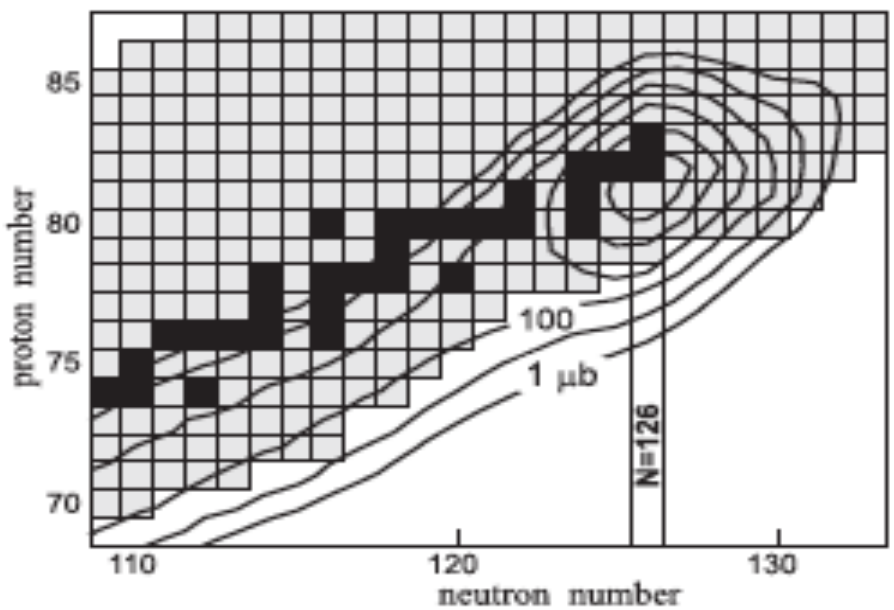
Multi-nucleon Transfer

- 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

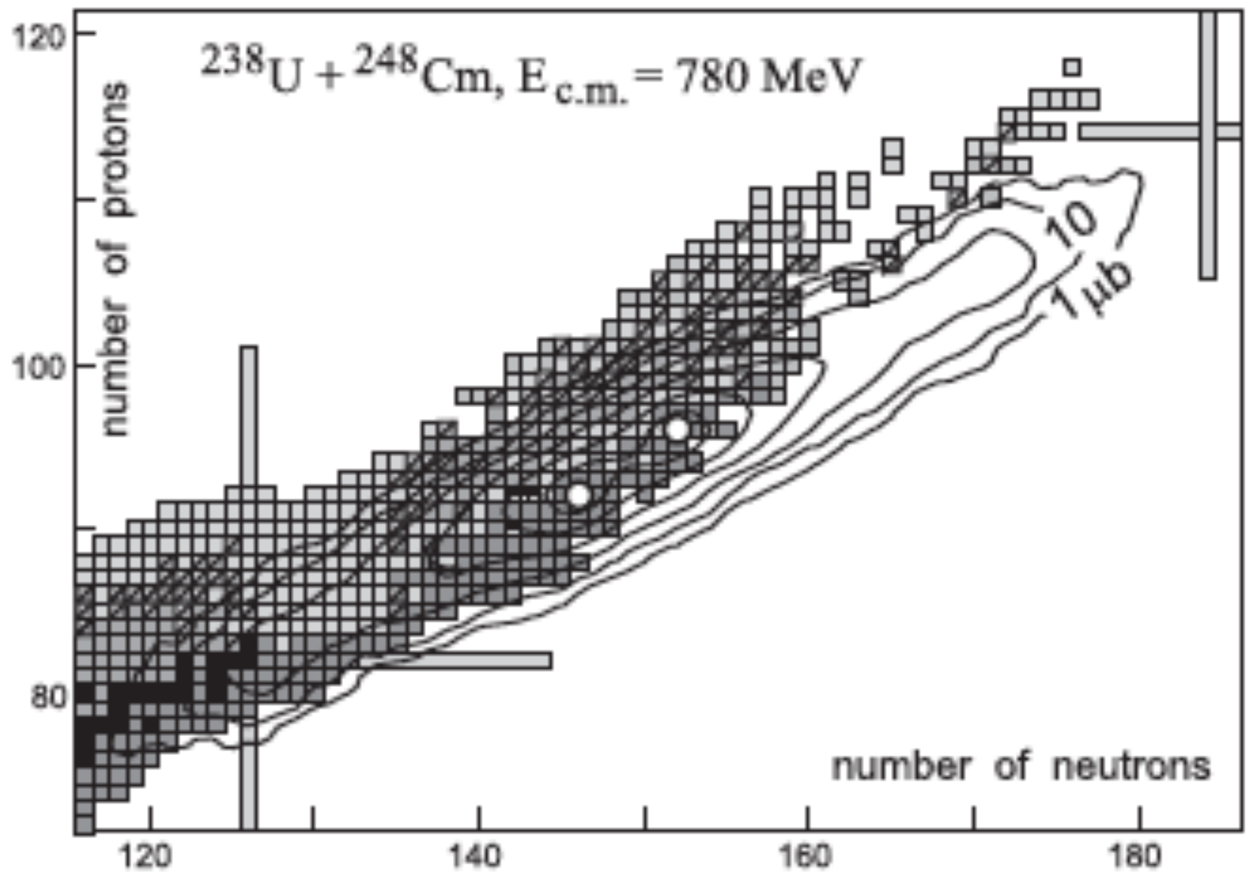
^{136}Xe + ^{208}Pb, E_{cm} =450 MeV



Reaction mechanisms
Nuclear spectroscopy
r-process waiting point

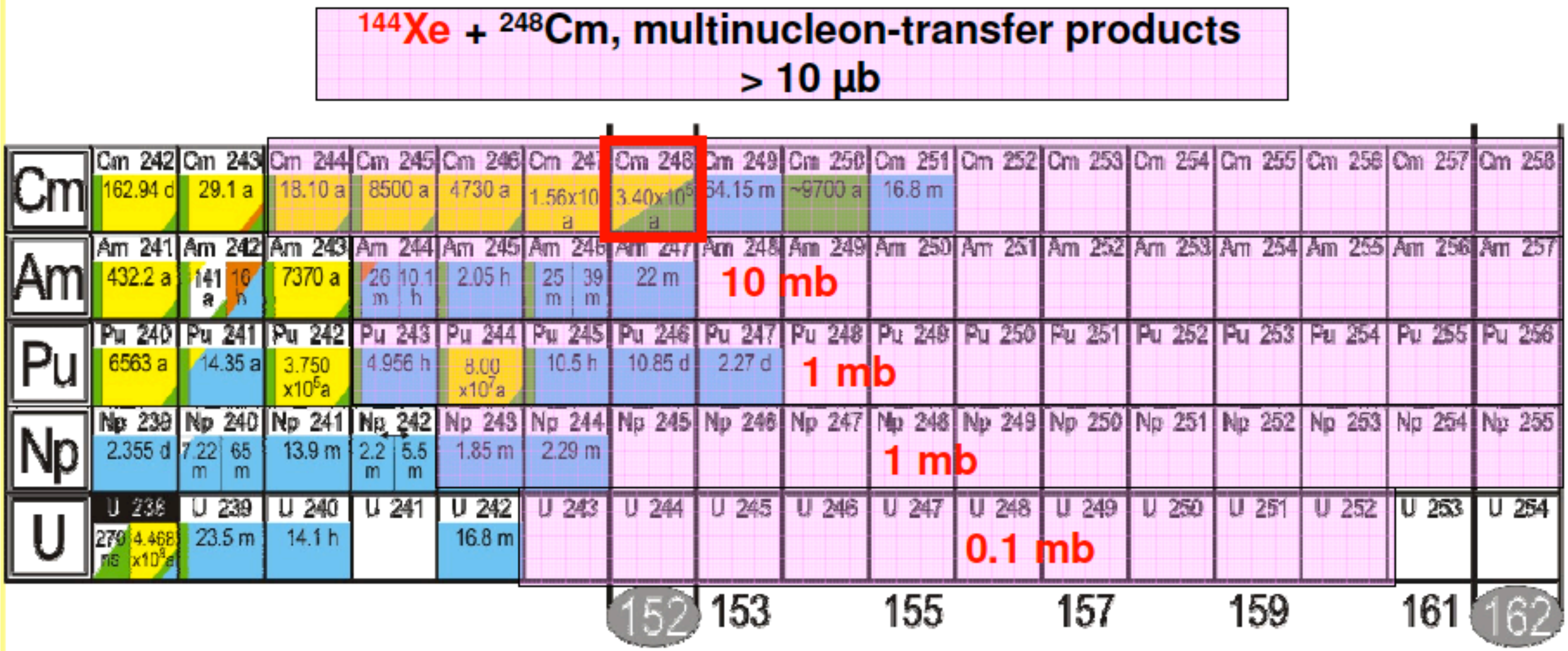
Gammasphere expts.
Radiochemistry expts.

New actinide nuclei



FUTURE: Multinucleon transfer in the heavy element region

radioactive ion-beam



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

SPIRAL 2 expects ^{144}Xe to be 5x10^{7}/s (5.7e5-day1);FRIB 5.6e3; CARIBU 2.3e3

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.