The Role of Energy in the Formation of the Heaviest Elements

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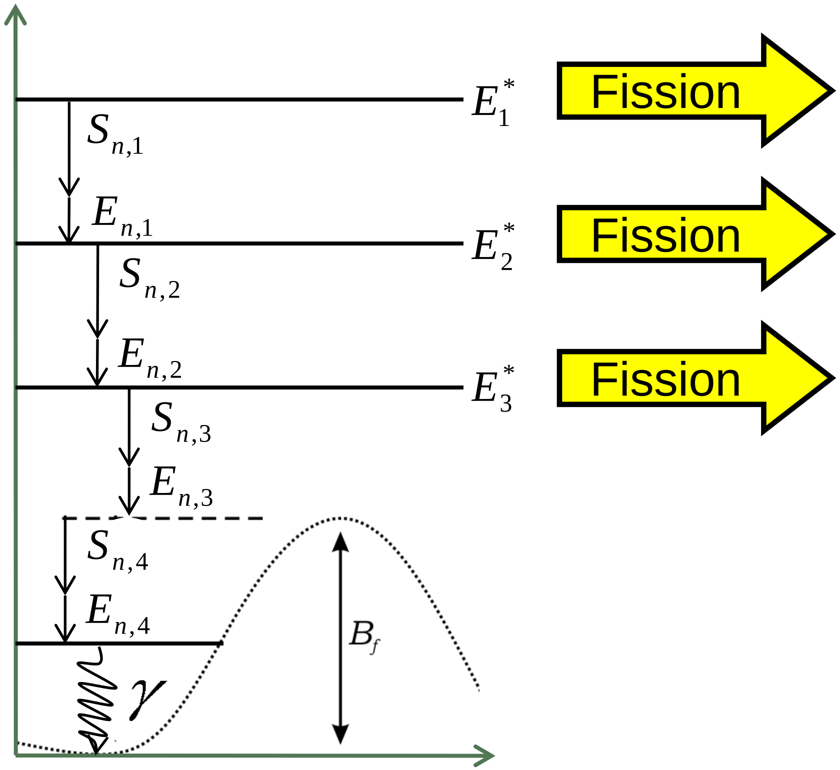
How do you make a heavy nucleus?

- The evaporation residue cross section can be written as:

$$\sigma = \sigma_{\text{cap}} P_{\text{CN}} W(E^*, l)$$

$$= \sigma_{\text{cap}} P_{\text{CN}} \prod_{i=1}^{x} \left(\Gamma_{\text{n}} / \Gamma_{\text{tot}} \right)_i$$

- $W(E^*, l)$ is the survival probability, which can be calculated from the decay widths: Γ_{n}, Γ_{f}, Γ_{α}, etc.



$$\boxed{\Gamma_{\text{n}} / \Gamma_{\text{f}} \propto \exp[-(B_{\text{n}} - B_{\text{f}}) / T]}$$

Current and Future History of Element 120

- JINR studied the $^{244}Pu(^{58}Fe, 4n)^{298}120$ reaction and reported an upper limit cross section of 0.4 pb (0.74 pb at 84% confidence).

- GSI Experiments:
  - $^{248}Cm(^{54}Cr, 4n)^{298}120$
    - Compare with $^{248}Cm(^{48}Ca, 4n)^{292}116$: $\sigma_{EVR} \approx 3.3$ pb
  - $^{249}Cf(^{50}Ti, 4n)^{295}120$

- Other reactions have been proposed:
  - $^{252}Cf(^{50}Ti, 4n)^{298}120$
  - $^{238}U(^{64}Ni, 4n)^{298}120$

^{48}Ca and ^{54}Cr Induced Reactions

$^{162}Dy(^{48}Ca, xn)^{210-x}Rn$

$^{162}Dy(^{54}Cr, xn)^{216-x}Th$

$^{248}Cm(^{48}Ca, xn)^{296-x}116$

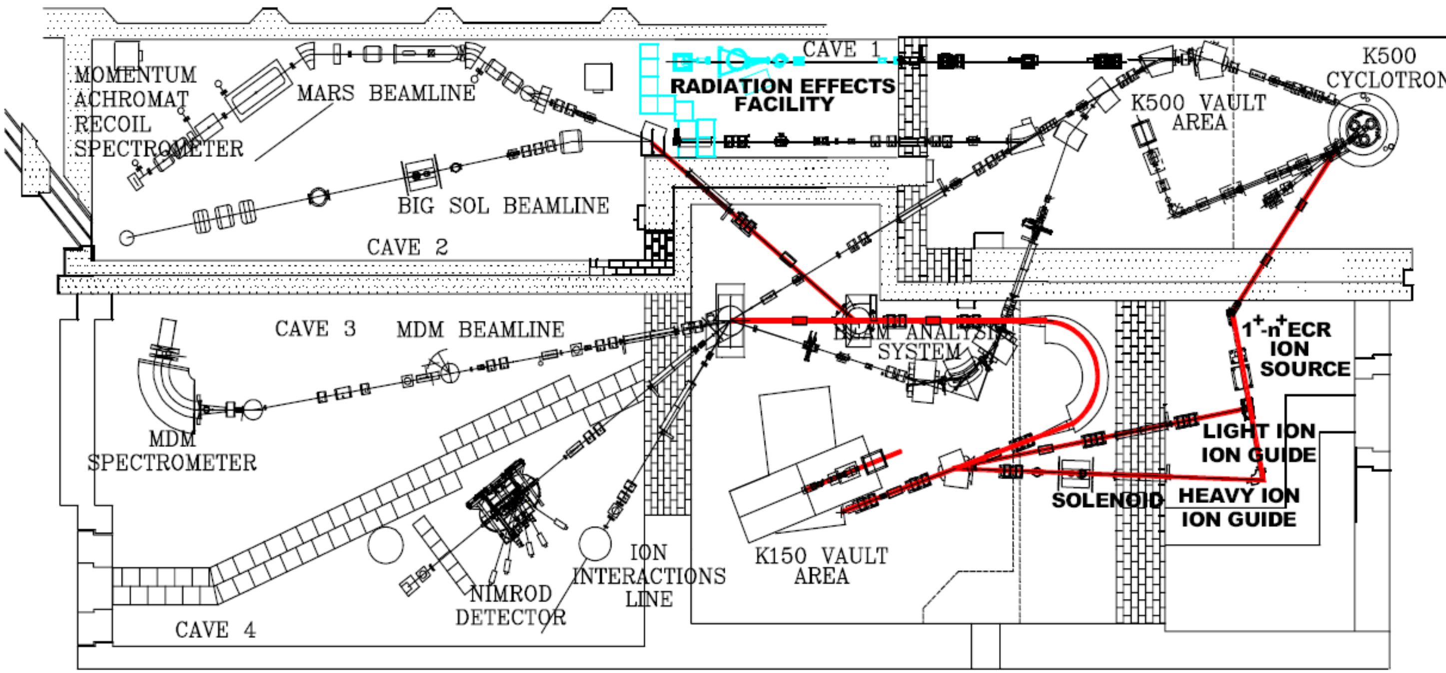
$^{248}Cm(^{54}Cr, xn)^{302-x}120$

Reaction	Product	N_{CN}	E_{cm} - B_{Coul}	E^*(CN)	$E^*(CN) - \Sigma(B_{n,i})$
$^{162}Dy(^{48}Ca, 4n)$	^{206}Rn	124	5.46 MeV	48 MeV	15.63 MeV
$^{162}Dy(^{54}Cr, 4n)$	^{212}Th	126	10.17 MeV	50 MeV	15.76 MeV
$^{248}Cm(^{48}Ca, 4n)$	$^{292}116$	180	9.58 MeV	41 MeV	15.48 MeV
$^{248}Cm(^{54}Cr, 4n)$	$^{298}120$	182	12.33 MeV	43 MeV	15.86 MeV

Column 4 shows the difference E_{cm} – B, where E_{cm} is the center of mass projectile energy and B is the average interaction (representing sum of Coulomb, centripetal, nuclear potentials) barrier height. E^*_{CN} is the excitation energy of the CN system. Column 6 gives the remaining excitation energy of a nucleus following emission of 4 neutrons each with binding energy S_n. Values were calculated based on estimated projectile energy needed to remove 4 neutrons, leaving the residual nucleus with excitation energy below either the S_n or B_f, whichever is lower in energy.

Upgraded Capabilities at Texas A&M

- As part of an upgrade sponsored principally by DOE, the K150 88" cyclotron is being recommissioned.



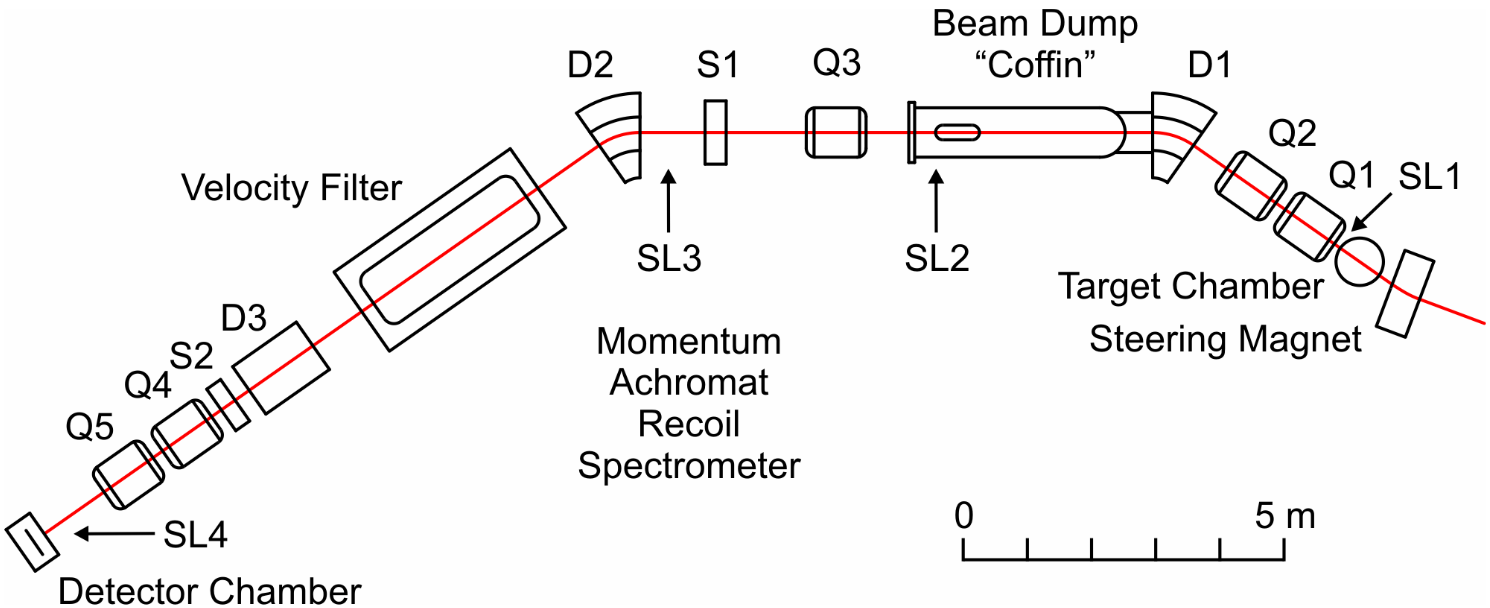
Supplied by 6.4-GHz ECR

Supplied by 14.5-GHz ECR

Figure 1. Layout for upgraded TAMU Facility. New additions are shown with red lines. The relocated SEE line is shown in light blue. High-intensity stable beams from the re-commissioned K150 Cyclotron will be used with ion guide techniques to produce high quality reaccelerated rare-ion beams from the K500 Cyclotron. K150 beams will be delivered to existing K500 experimental areas.

http://cyclotron.tamu.edu/facility_upgrade.pdf

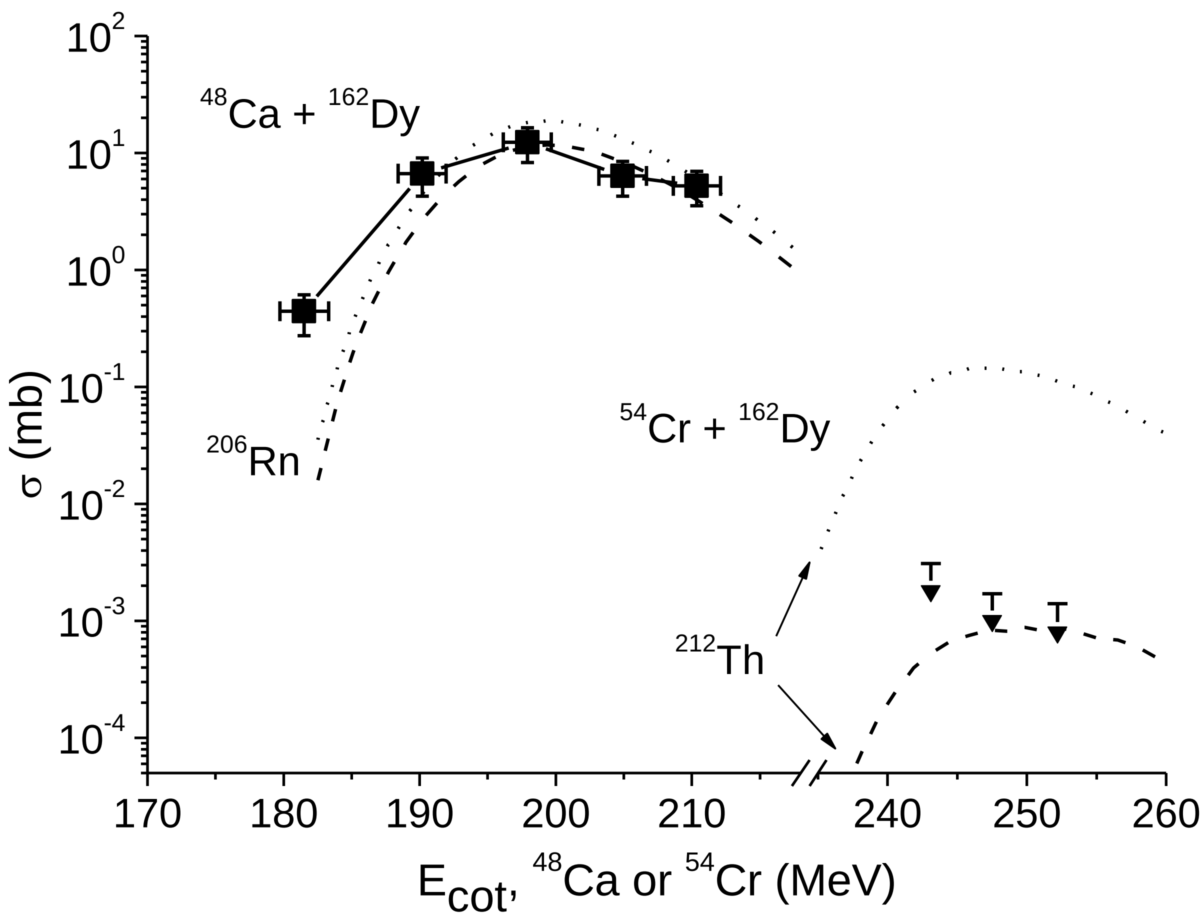
MARS



Device	Acceptance	$\Delta p/p$	$B\rho_{\mathrm{max}}$
MARS	9 msr	4%	1.8 T m
SHIP	~4 msr	10%	1.2 T m
BGS	45 msr	9%	2.5 T m

R.E. Tribble, R.H. Burch, and C.A. Gagliardi, NIMA 285, 441 (1989).
R.E. Tribble, C.A. Gagliardi, and W. Liu, NIMB 56/57, 956 (1991).

^{162}Dy(^{48}Ca,xn)$^{210-x}$Rn and ^{162}Dy(^{54}Cr,xn)$^{216-x}$Rn Excitation Functions



$$\frac{\sigma_{EVR}(^{206}Rn)}{\sigma_{EVR}(^{212}Th)} \geq 7.3\times10^3$$

$$P_{\rm CN} = \frac{\sigma_{\rm EVR}}{\sigma_{\rm cap}\prod_{i=1}^{x}\left(\Gamma_{\rm n}/\Gamma_{\rm tot}\right)_i}$$

$$\frac{P_{\rm CN}(^{48}{\rm Ca} + {}^{162}{\rm Dy})}{P_{\rm CN}(^{54}{\rm Cr} + {}^{162}{\rm Dy})} \geq 1.2$$

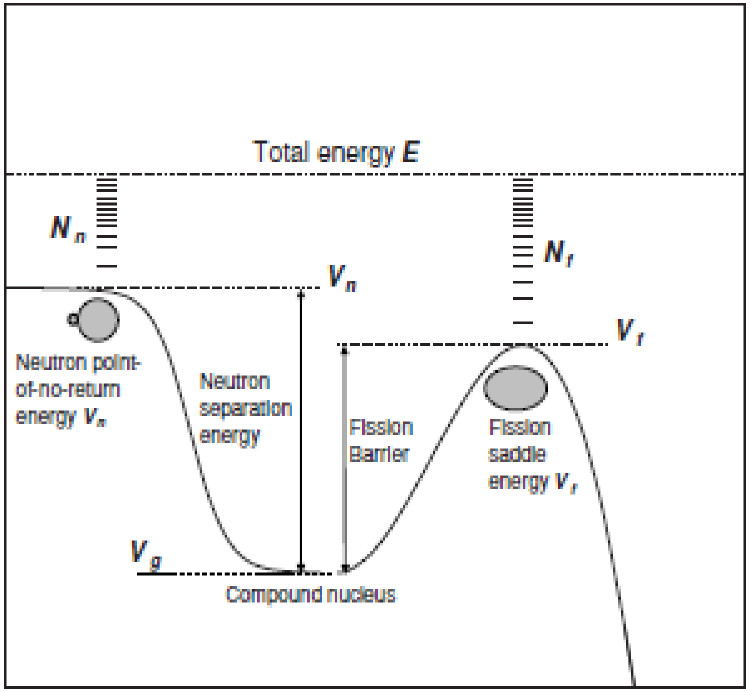
Dotted Lines: Theory *without* collective effects.

Dashed lines: Theory *with* collective effects.

Collective effects have a huge impact on the ^{216}Th CN!

Collective Effects

- The contribution of vibrations to the level density is likely much more significant than rotations. This is likely exacerbated by the high fissility of heavy nuclei.
- In the case of $^{212\text{-}216}$Th, these nuclei are almost spherical. The contribution of rotational states is small.



$$^{216}\mathrm{Th} \xrightarrow{-\mathrm{n}} {}^{215}\mathrm{Th} \xrightarrow{-\mathrm{n}} {}^{214}\mathrm{Th} \xrightarrow{-\mathrm{n}} {}^{213}\mathrm{Th} \xrightarrow{-\mathrm{n}} {}^{212}\mathrm{Th}$$

β_2: +0.008 −0.018 −0.052 −0.070 −0.070

P. Möller et al., Atom. Data Nucl. Data Tables 59, 185 (1995).

Summary of the ^{162}Dy Reactions

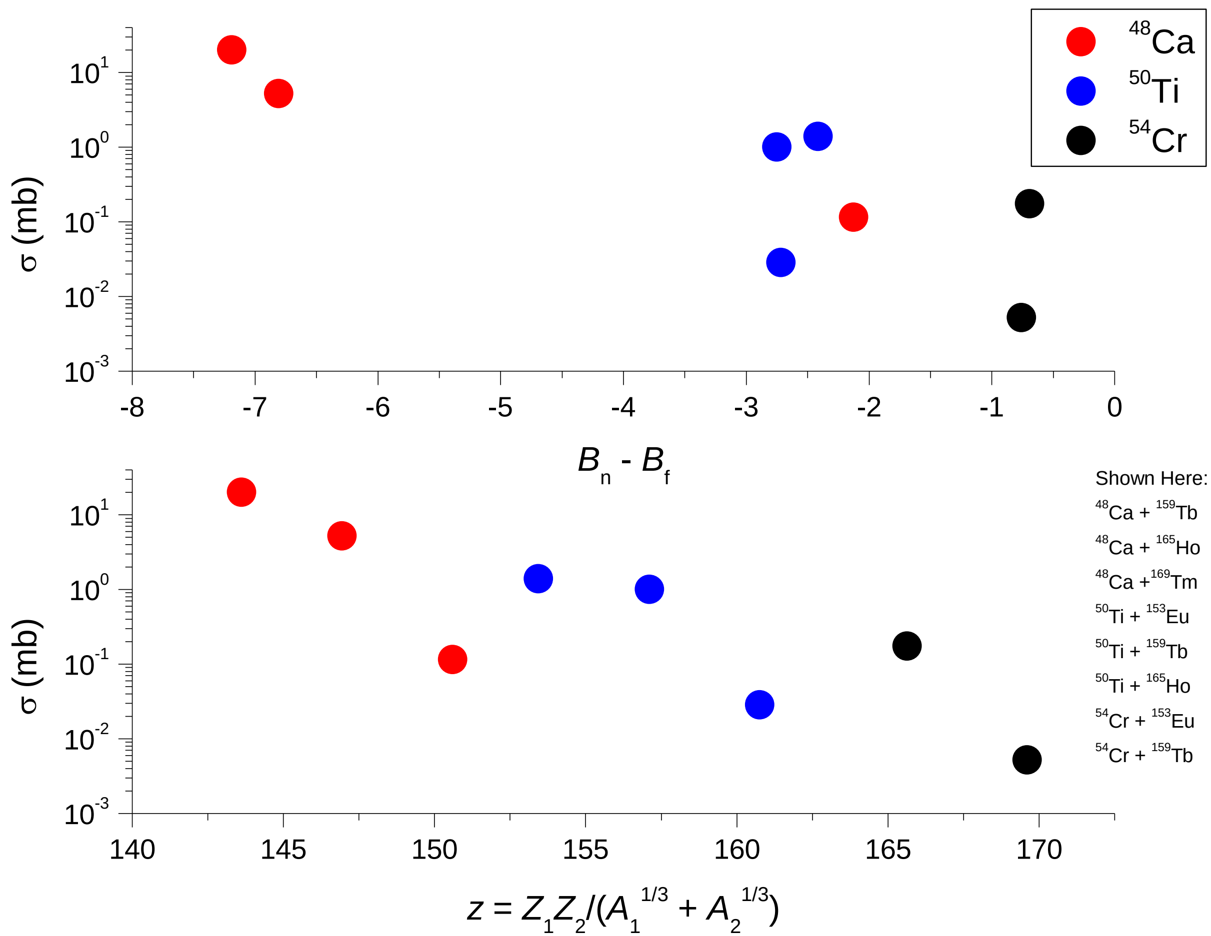
- Changing from ^{48}Ca to ^{54}Cr changed the cross section by $>7.3 \times 10^3$.

- The change in P_{CN} was >1.2, in line with calculations.
- A lower cross section would cause this limit to increase.

- The difference in survivability is estimated to be 7.8×10^3.
  - Of this, only ≈ 76 is due to the change in $B_n - B_f$.
  - $\Delta(B_n - B_f) \approx 6$ MeV
  - The remainder (>90) may be due to collective effects.

Effects of $B_n - B_f$ and z on Reactions with Odd-Z Targets

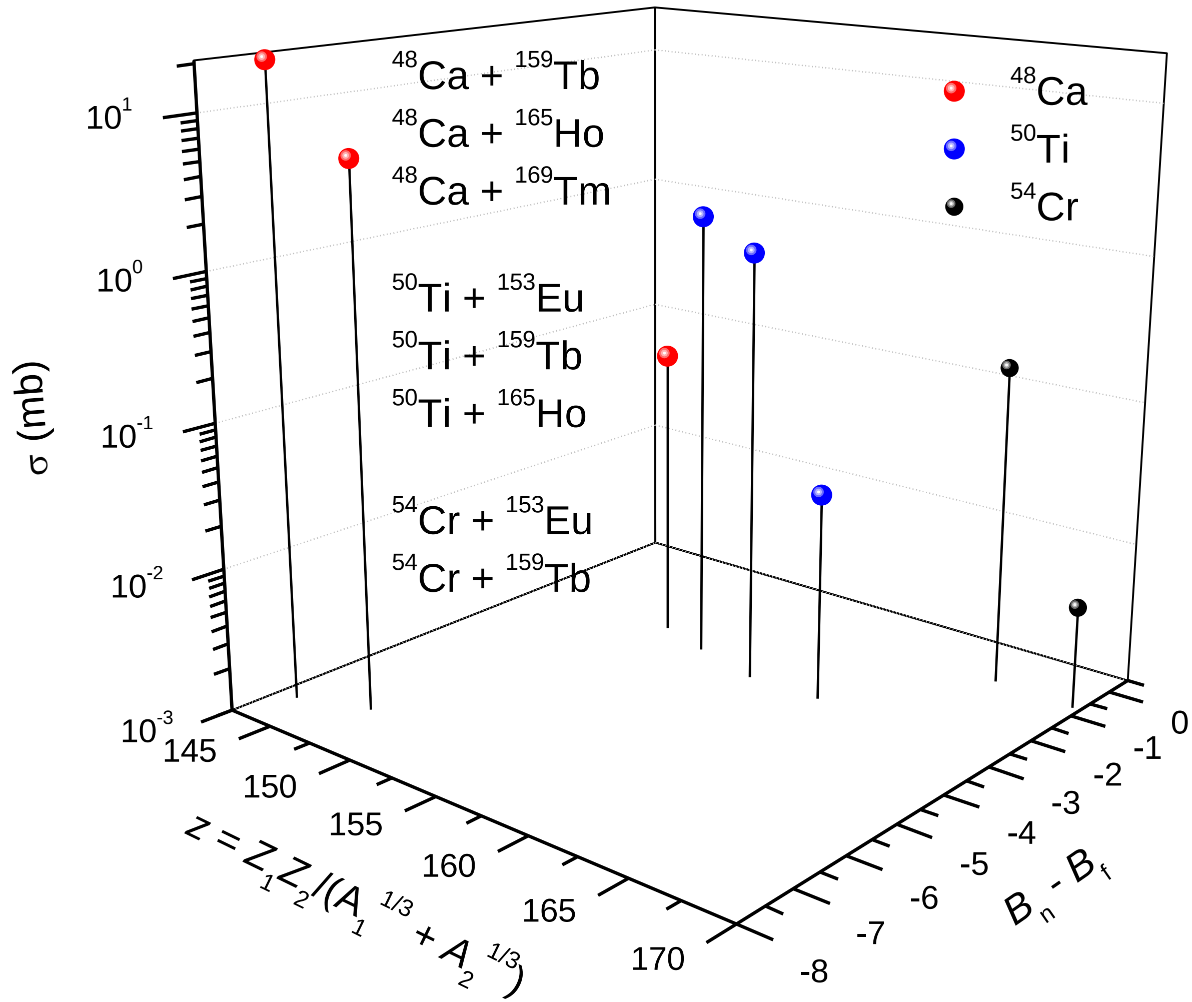
- The energetics of ^{54}Cr are much less favorable than ^{48}Ca.
- Not surprisingly, there is a strong dependence on the Coulomb parameter z.



V.I. Zagrebaev et al., http://nrv.jinr.ru/nrv/

Effects of $B_n - B_f$ and z on Reactions with Odd-Z Targets z

- The same data as the previous plots.



Cross Sections: V.I. Zagrebaev et al., http://nrv.jinr.ru/nrv/

Implications for the Production of Element 120

- The $^{248}Cm(^{54}Cr, 4n)^{298}120$ reaction has three serious problems:
  - A reduction in P_{CN} relative to $^{248}Cm(^{48}Ca, 4n)^{298}120$. (Beam changed from ^{48}Ca to ^{54}Cr).
  - The high fissility of the compound nucleus.
  - (Possibly) No increase in survivability due to the predicted closed shell at $N = 184$.
- Our data suggests that predictions of σ_{EVR} on the order of tens of femtobarns are reasonable.

- $^{249}Cf(^{50}Ti, 4n)^{295}120$ may be more feasible due to a more favorable P_{CN}.

Summary

- The formation of heavy element with projectiles beyond ^{48}Ca may be extremely difficult.

- For these purposes, ^{48}Ca is effectively a radioactive beam.

- The success of the search for element 120 depends on:
  - The strength of the shell correction energy for Z = 120.
  - The decrease in P_{CN} with increasing projectile mass.
  - The influence of vibrational modes.

Future Work

- We will investigate ^{50}Ti + ^{162}Dy in Sept. 2011.
- We will move to odd-*Z* targets in Oct. 2011.
- We want to move down the periodic table toward transactinides.
- The K150 will soon be online and will provide increased intensity for medium-mass beams.

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