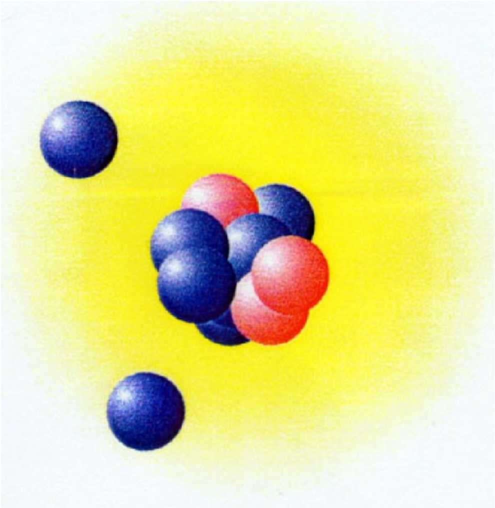
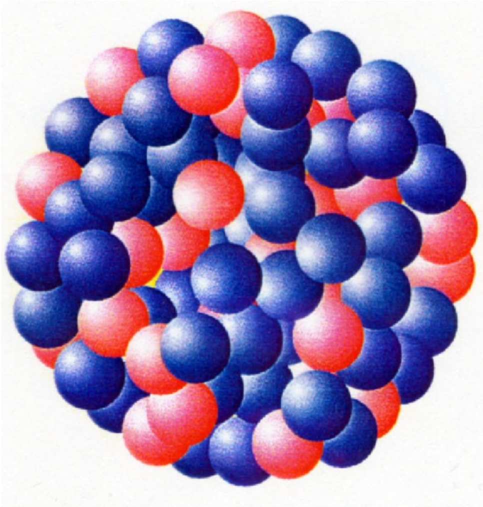
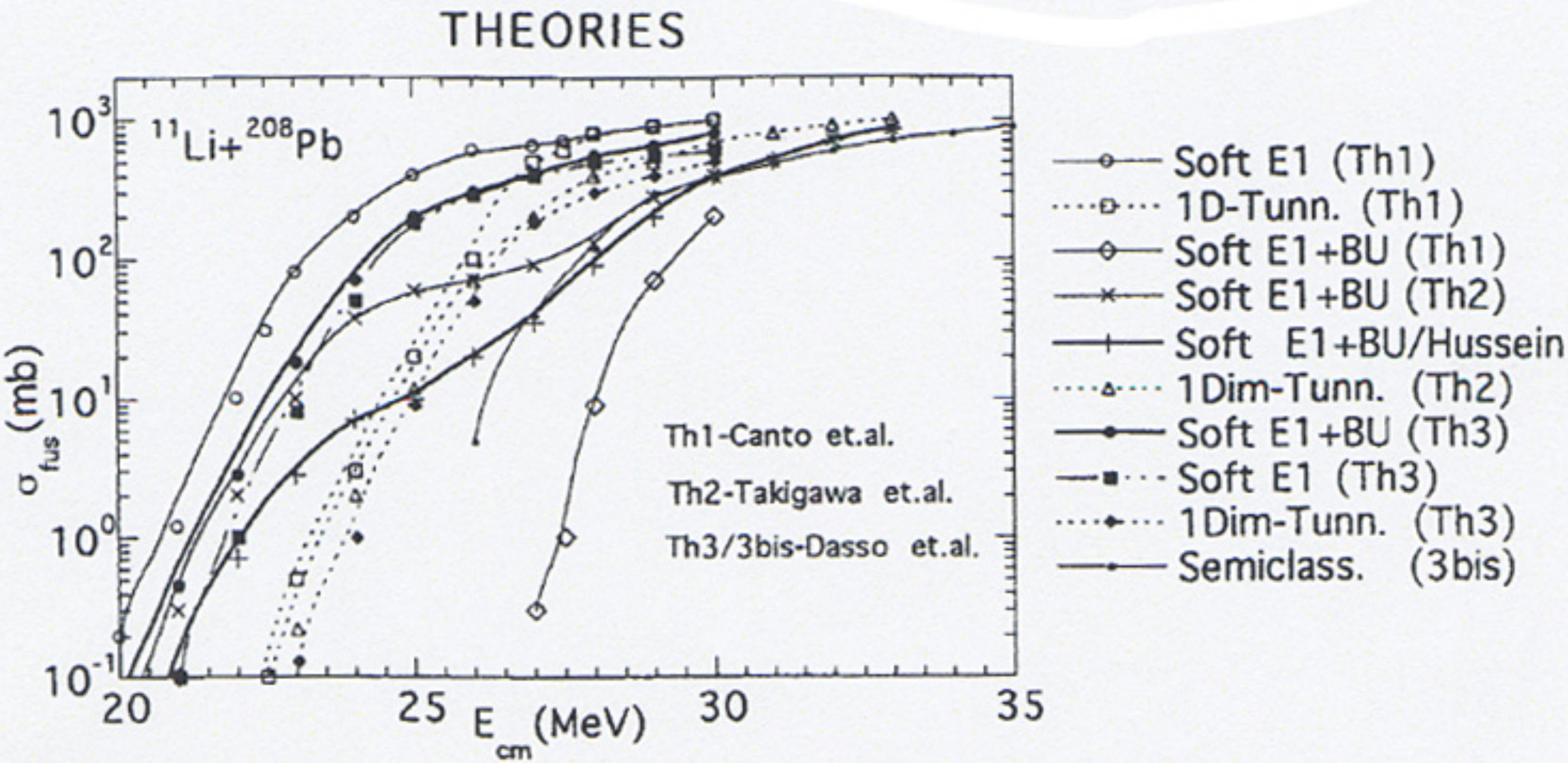
# 3 Problems

W. Loveland
Oregon State University

# The fusion of $^{11}Li + ^{208}Pb$

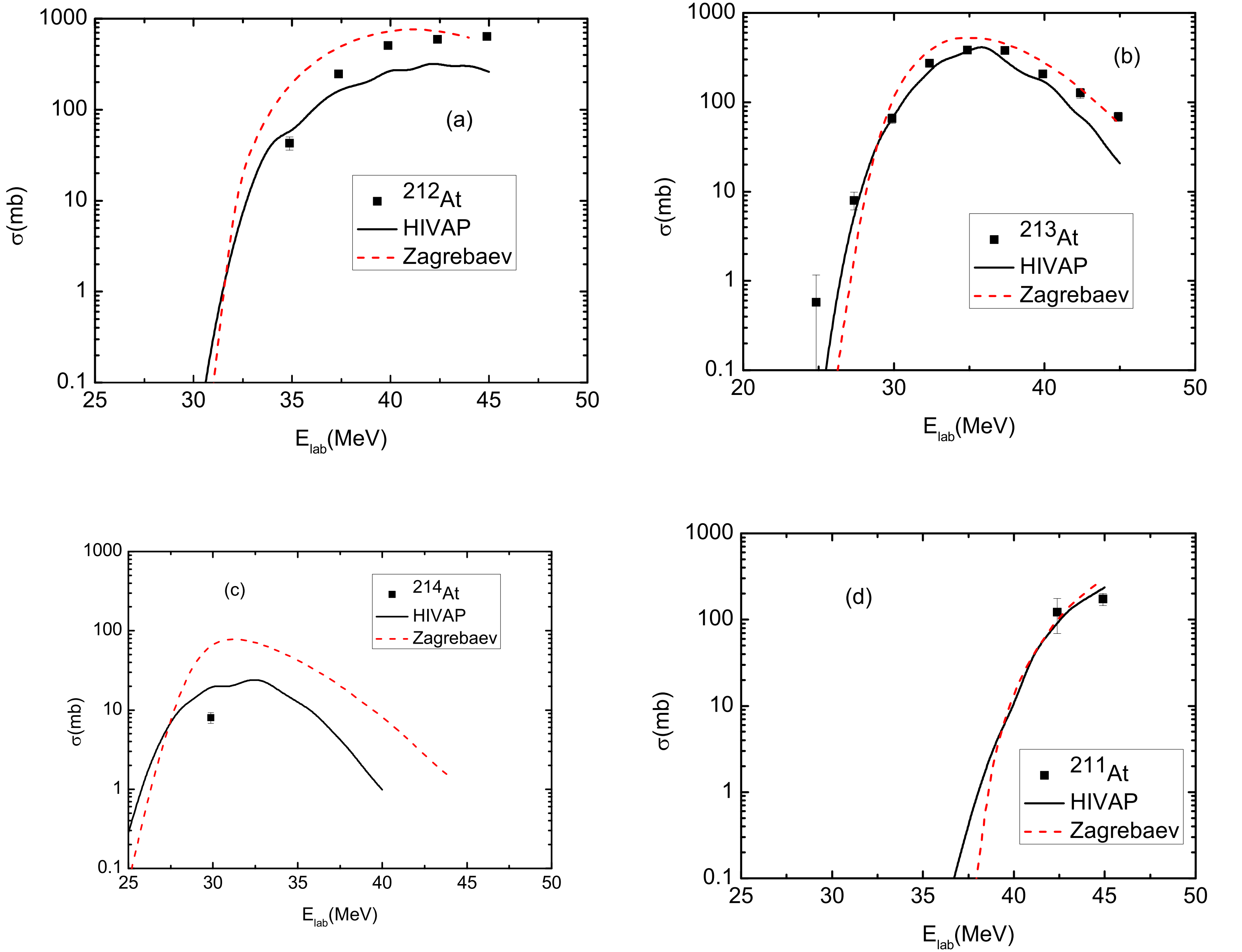


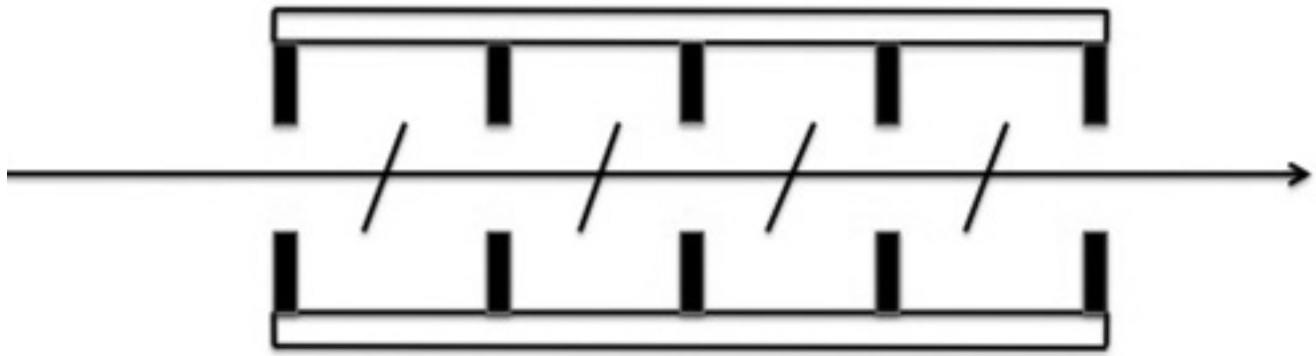




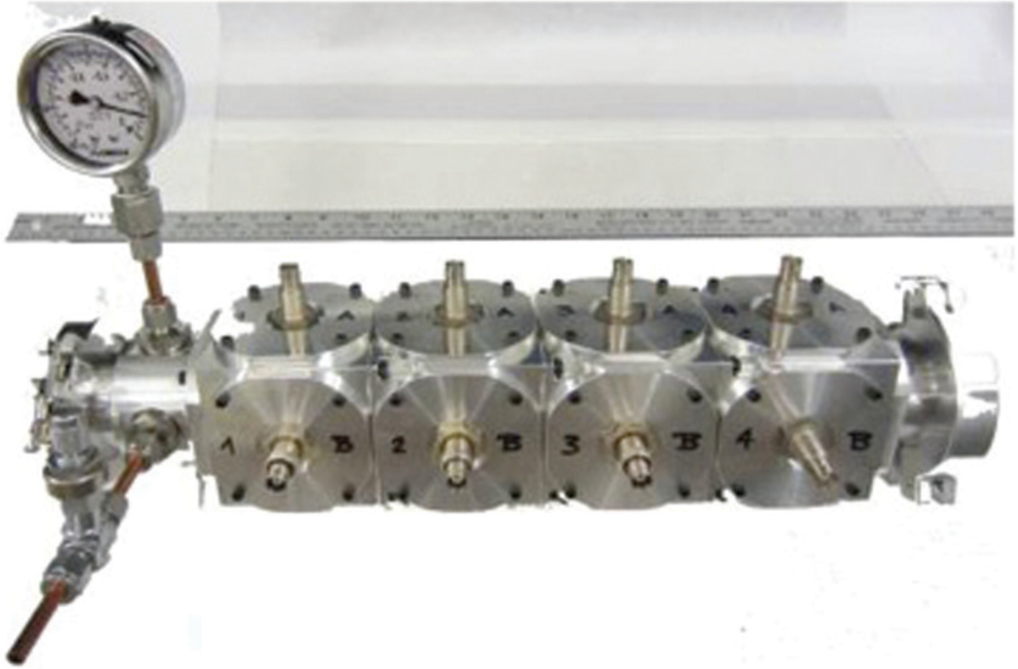

Dasso=CC, rest are optical model approaches

# $^{9}Li + ^{208}Pb$—Statistical models describe data

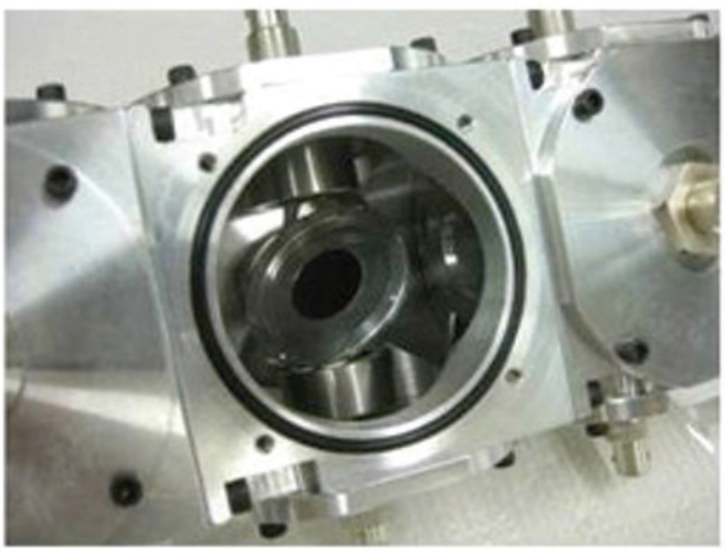




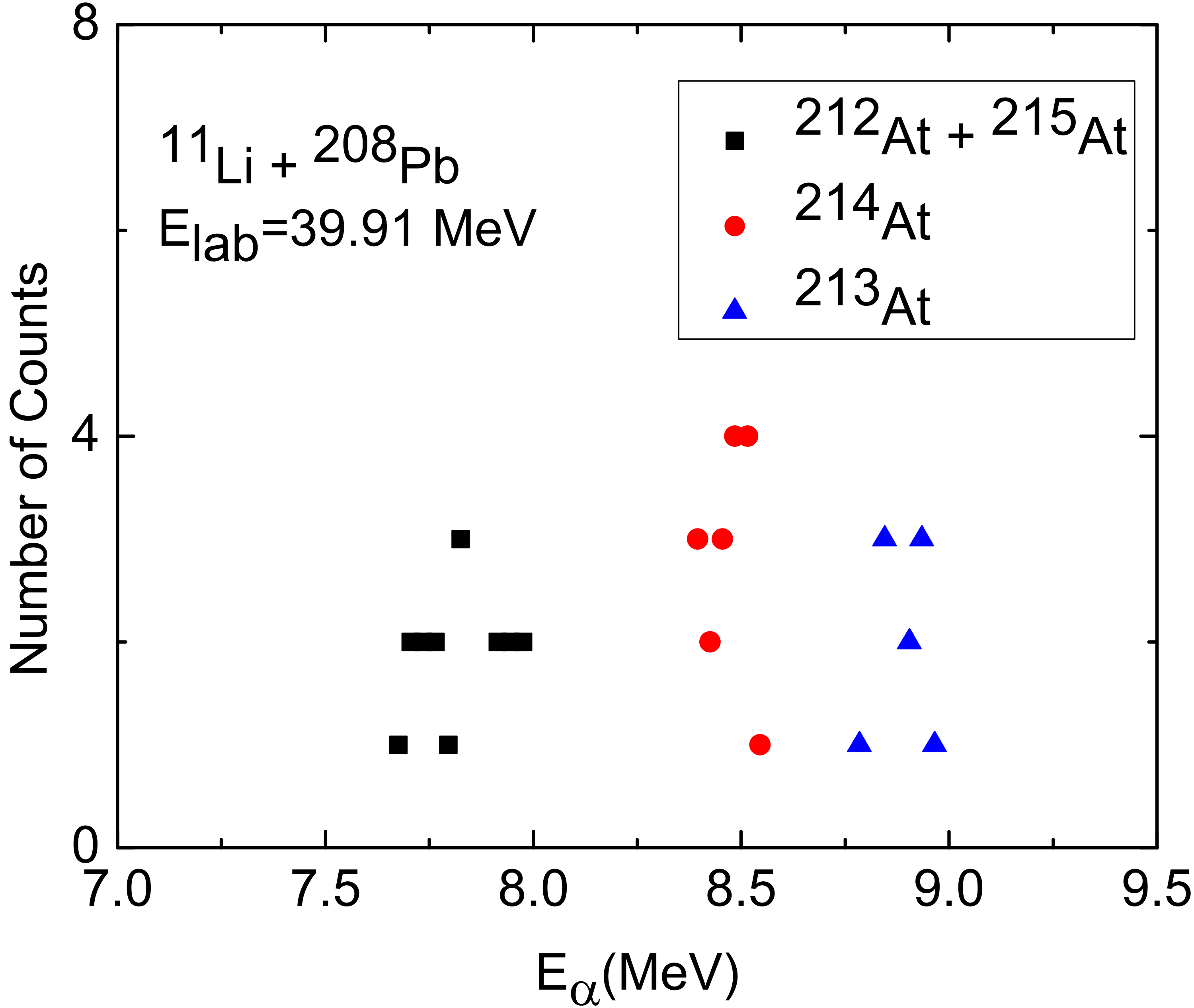
(a)



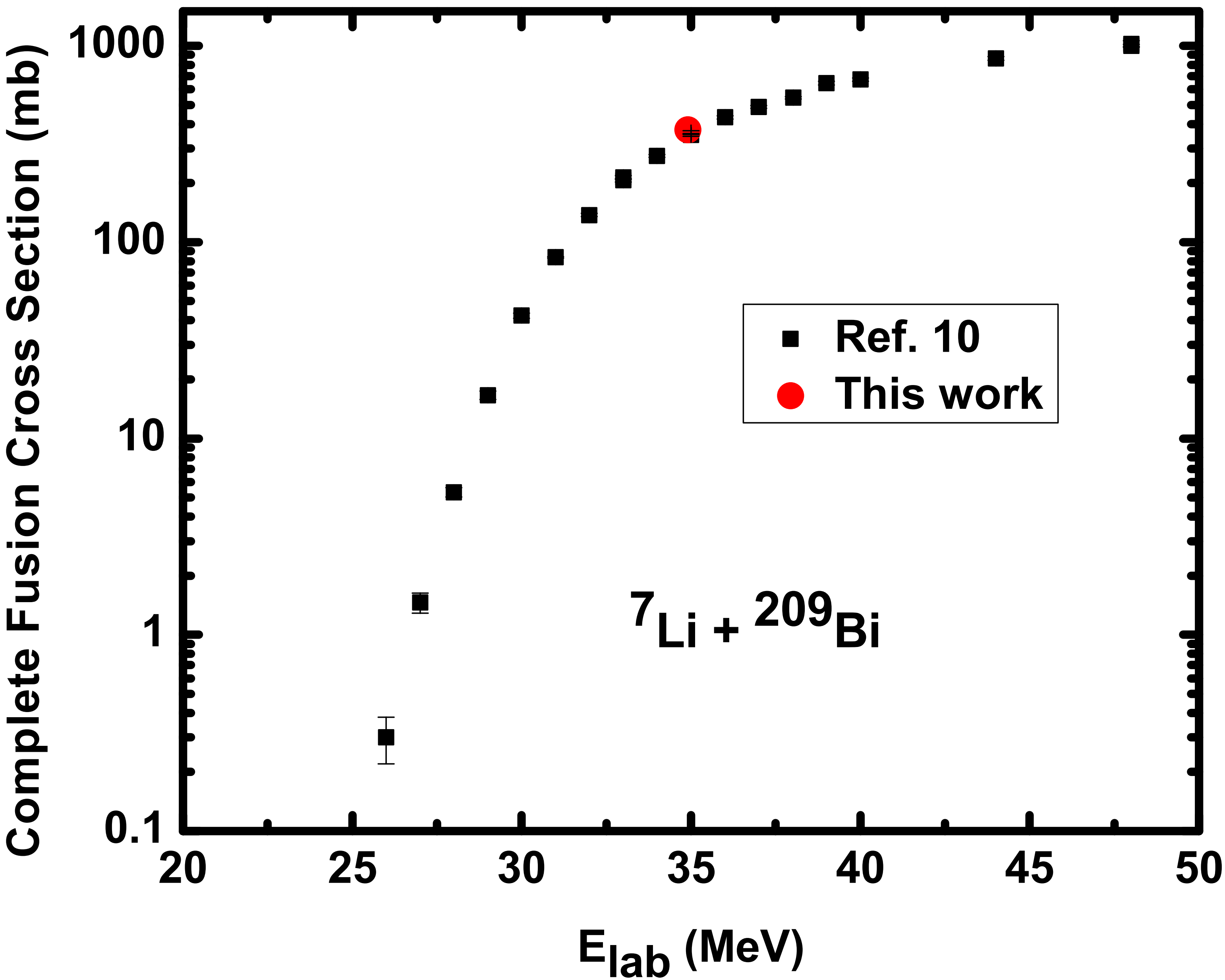

b)



(c)



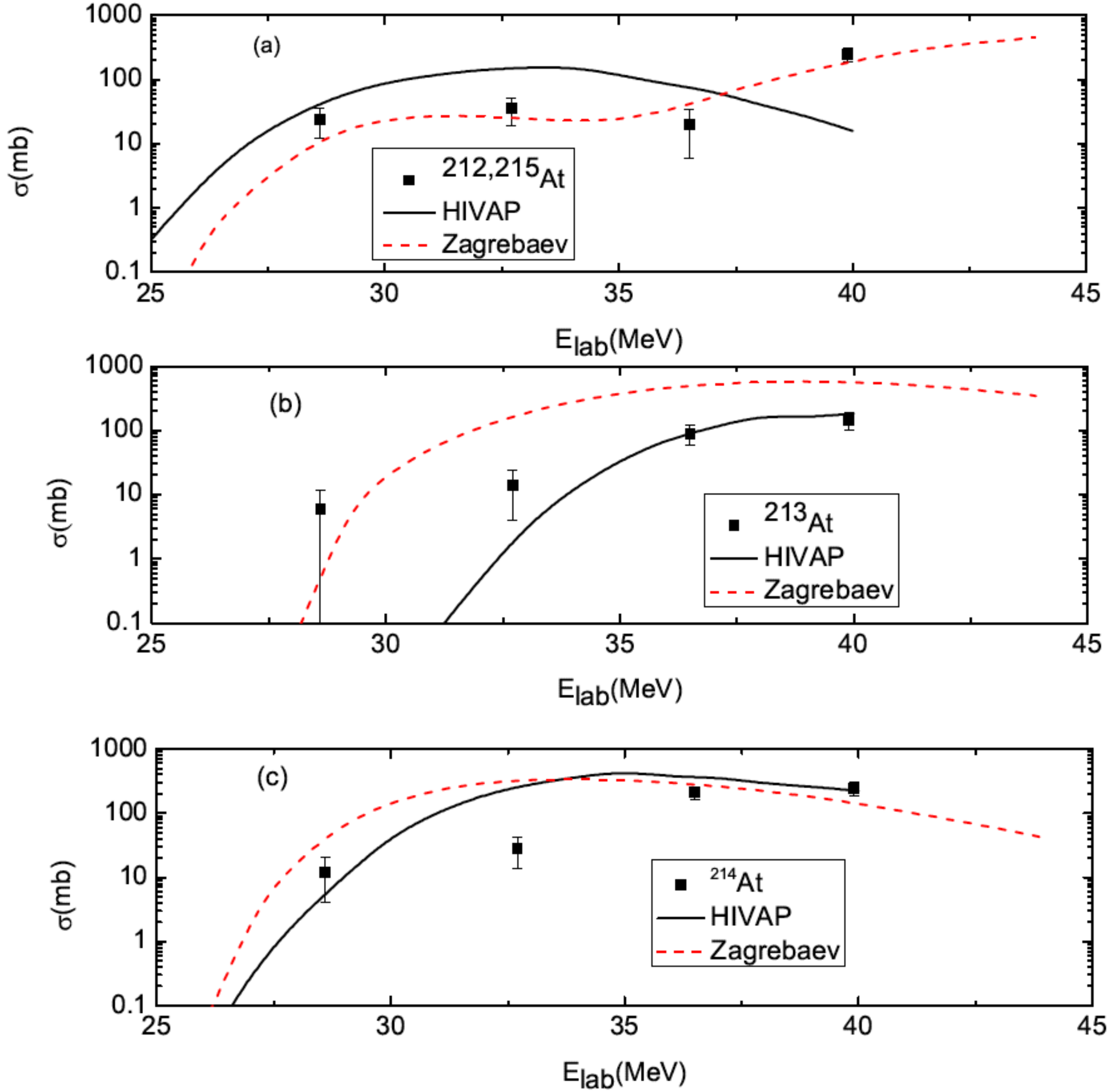
8
4
0
7.0
7.5
8.0
8.5
9.0
9.5
Number of Counts
$E_\alpha$(MeV)
$^{11}Li + ^{208}Pb$
$E_{lab}$=39.91 MeV
$^{212}At + ^{215}At$
$^{214}At$
$^{213}At$



Complete Fusion Cross Section (mb)
1000
100
10
1
0.1
20
25
30
35
40
45
50
$E_{lab}$ (MeV)
Ref. 10
This work
$^{7}Li + ^{209}Bi$

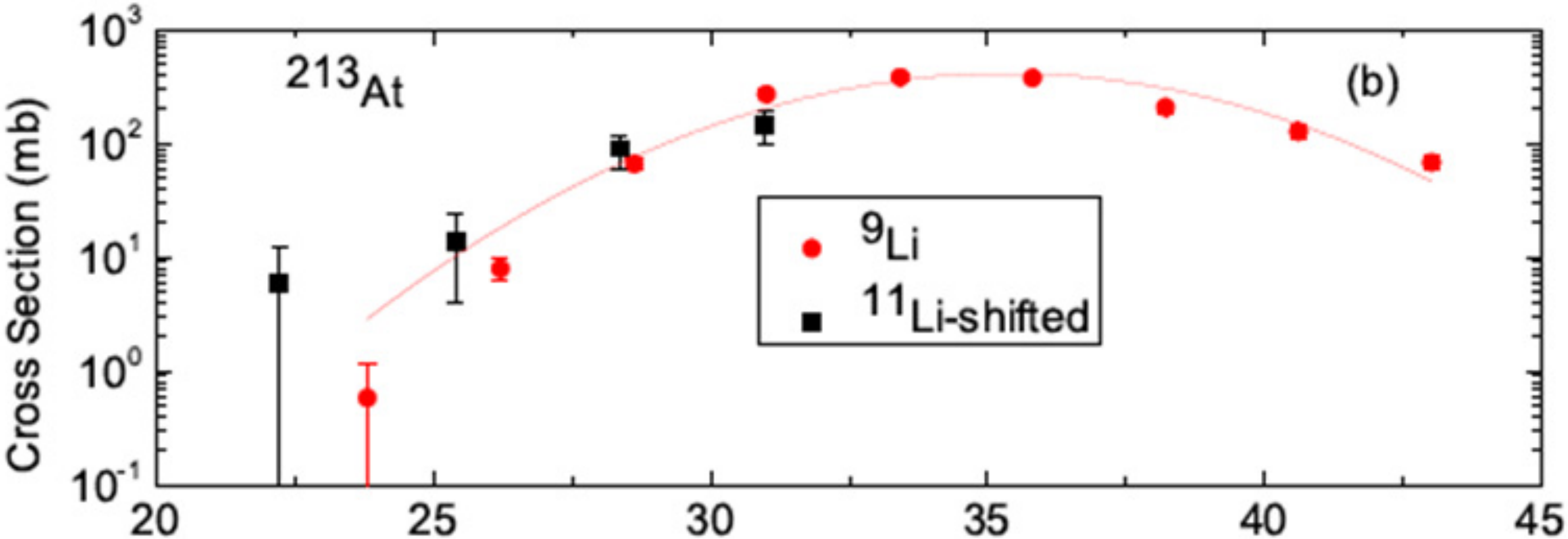
# $^{11}Li + ^{208}Pb$

## CF → $^{212,215}At$, $^{214}At$




(not so good)

ICF ➔ $^{213}$At


213At
(b)
Cross Section (mb)
10^3
10^2
10^1
10^0
10^-1
20
25
30
35
40
45
9Li
11Li-shifted

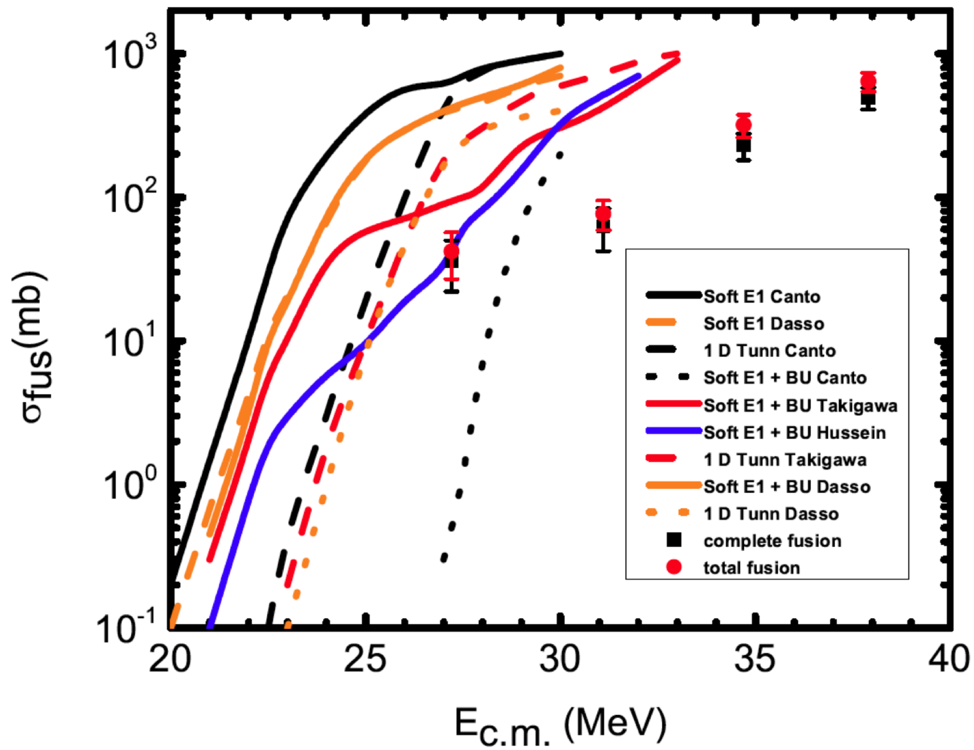
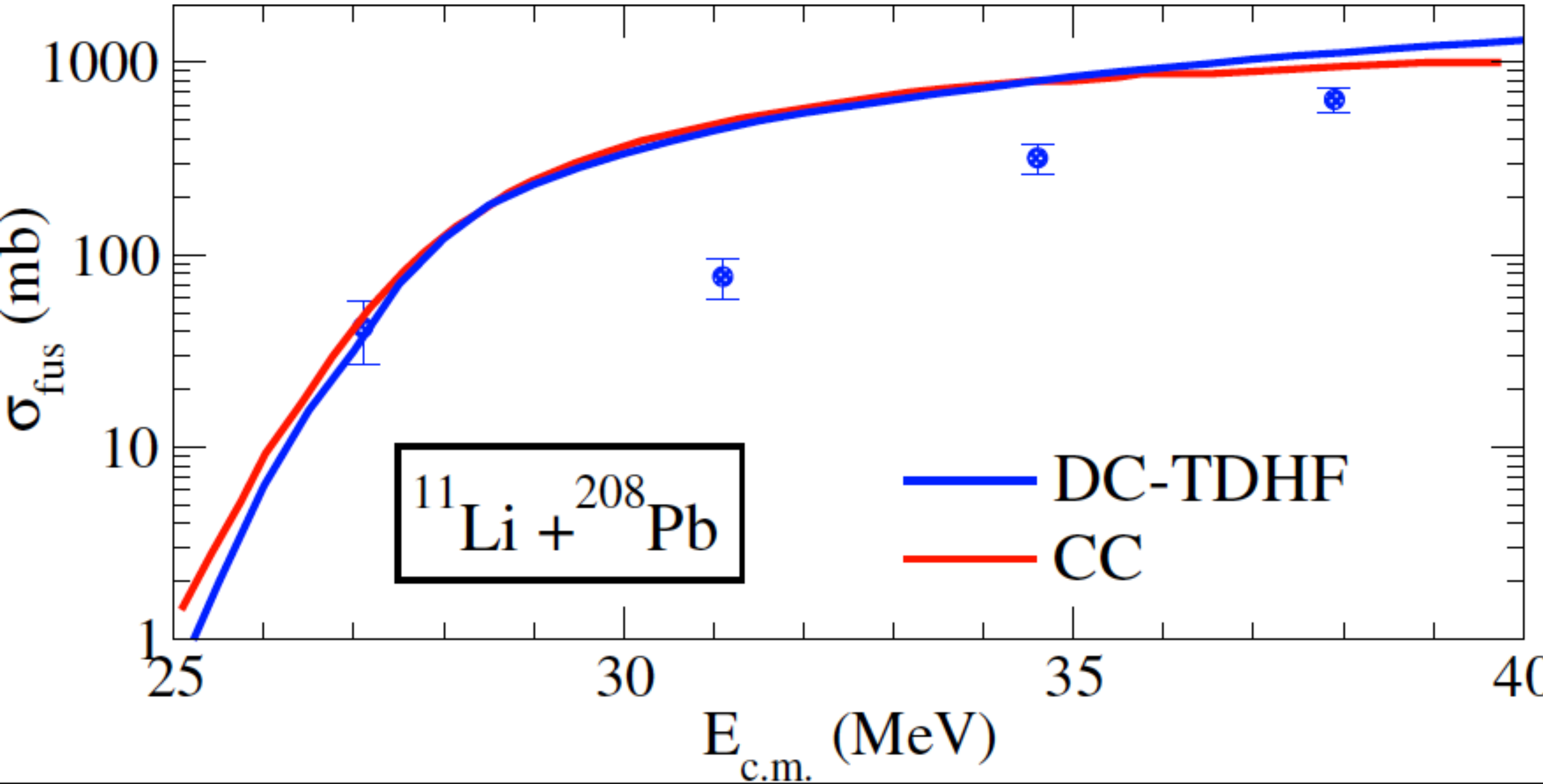



FIG. 11: (Color online)Comparison of various theoretical predictions for the $^{11}Li + ^{208}Pb$ fusion excitation function, after [1, 2], with our data.




S. Umar (private communication)

# What does all this mean?

- Why does the DC-TDHF "work"?
- Why are so many models wrong?

# Production of Heavy Elements in Complete Fusion Reactions

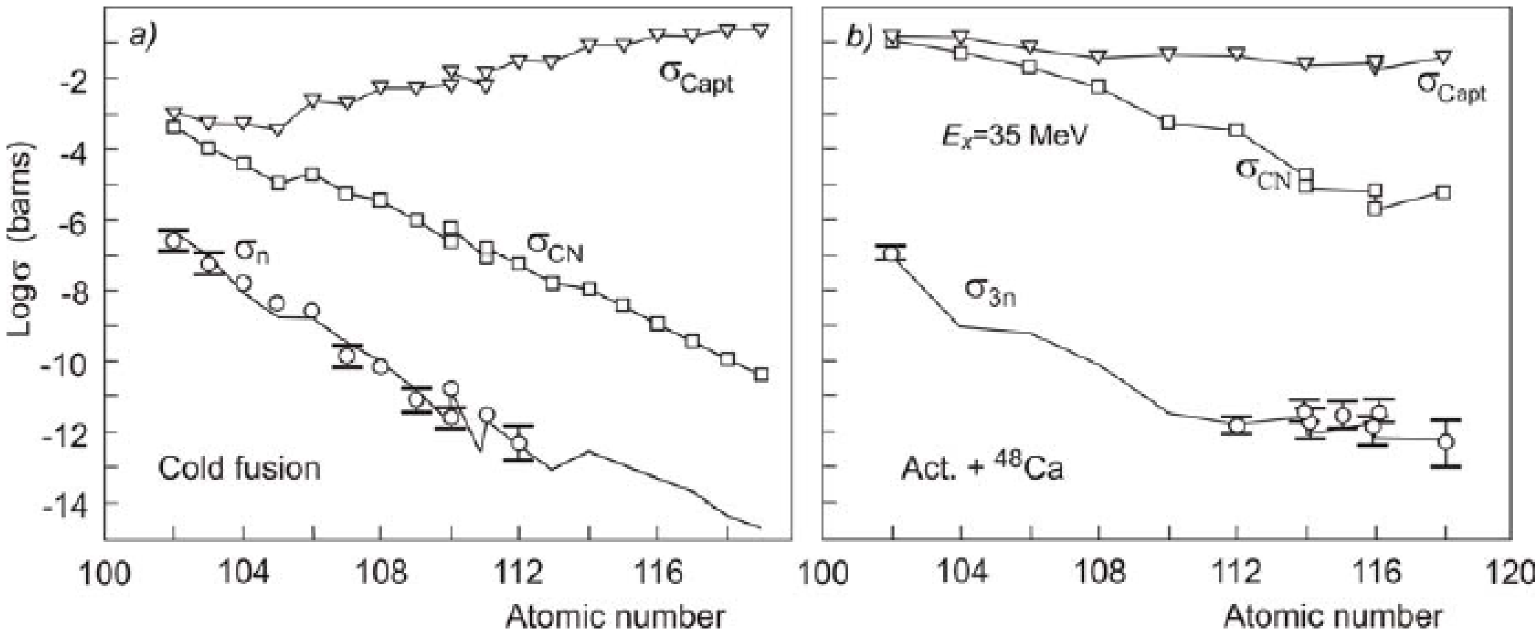
$$\sigma_{\mathrm{EVR}}(E_{\mathrm{c.m.}}) = \sum_{J=0}^{J_{\max}} \sigma_{\mathrm{CN}}(E_{\mathrm{c.m.}}, J) W_{\mathrm{sur}}(E_{\mathrm{c.m.}}, J),$$

where

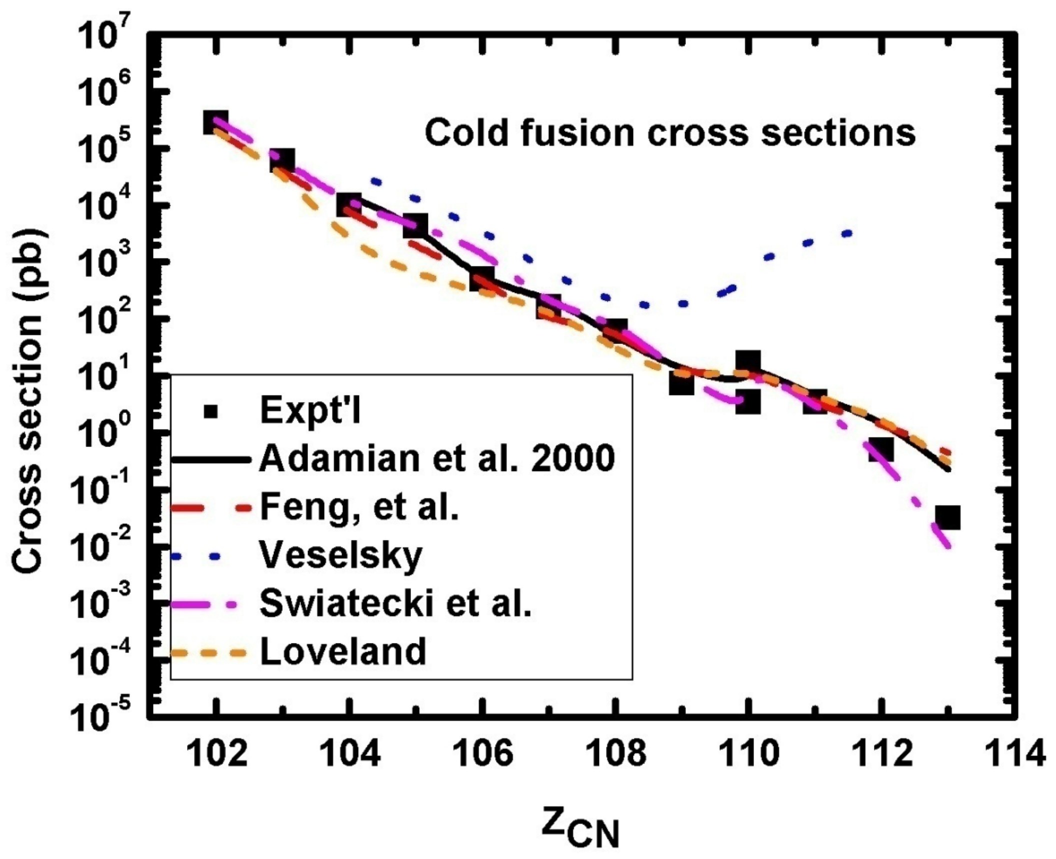
$$\sigma_{\mathrm{CN}}(E_{\mathrm{c.m.}}) = \sum_{J=0}^{J_{\max}} \sigma_{\mathrm{capture}}(E_{\mathrm{c.m.}}, J) P_{\mathrm{CN}}(E_{\mathrm{c.m.}}, J),$$

- 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

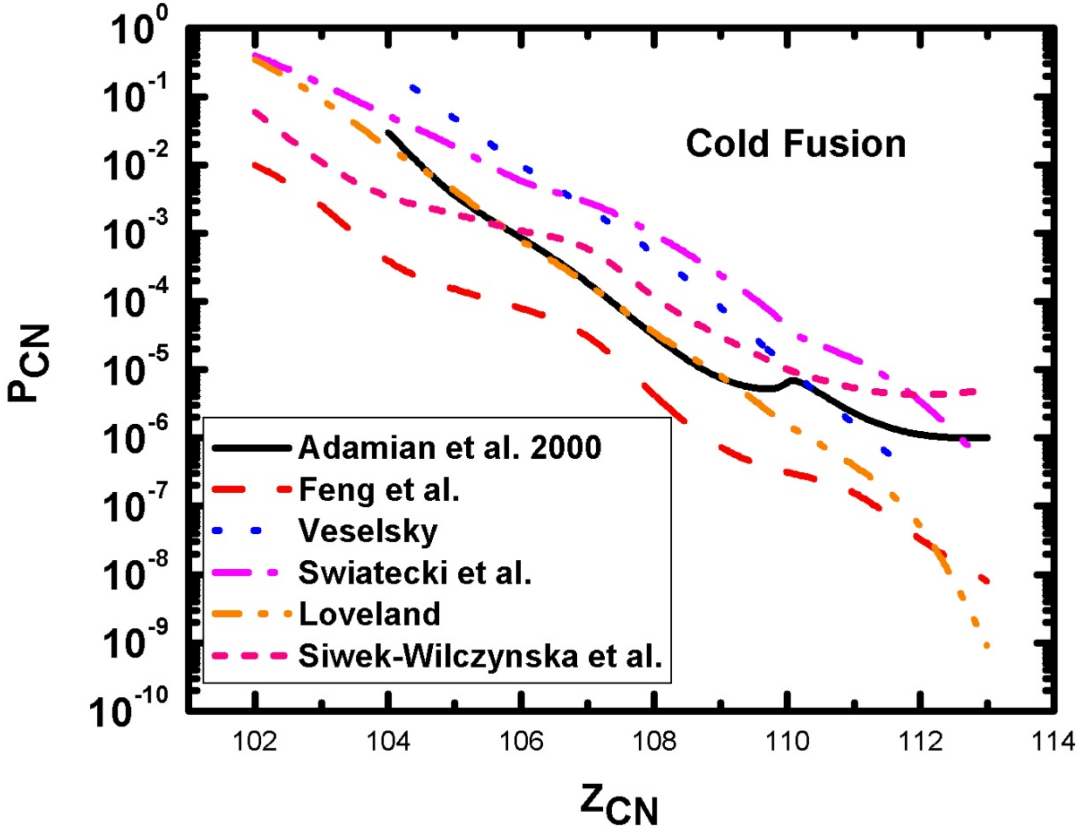
# How well can we describe observations?



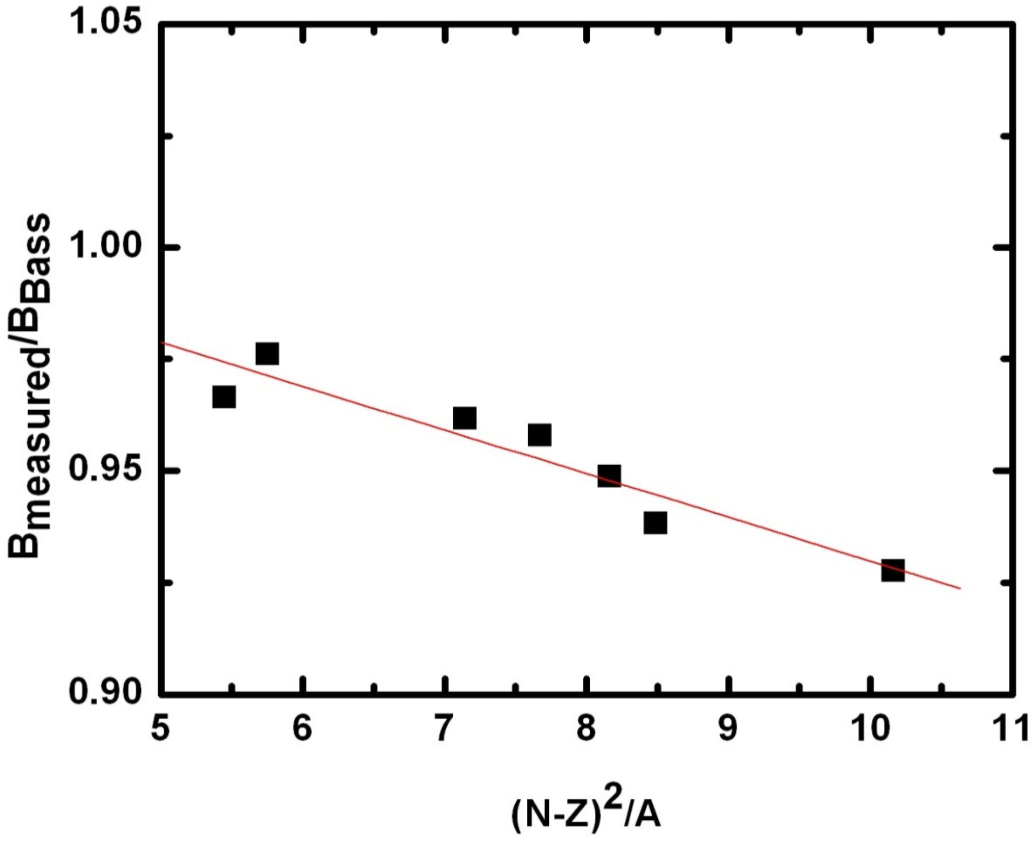
# Let's look at this more carefully



# Despite correctly predicting $\sigma_{EVR}$ correctly, the values of $P_{CN}$ (and $W_{sur}$ )differ significantly



# Effect of n-richness on capture cross sections

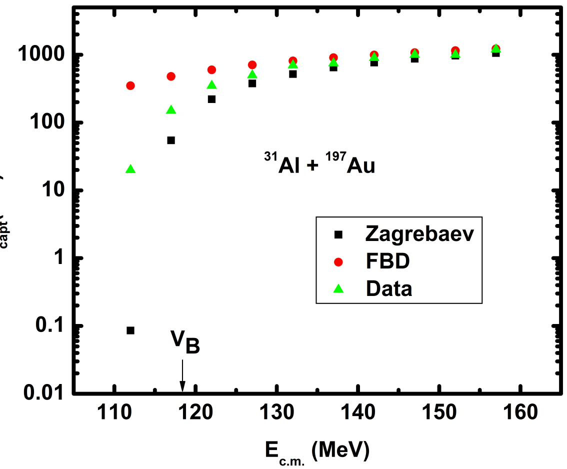


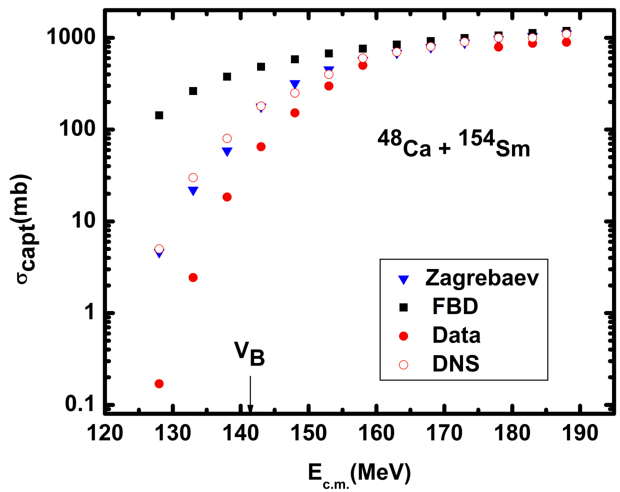

W. Loveland, et al., PRC 74, 044607 (2006)

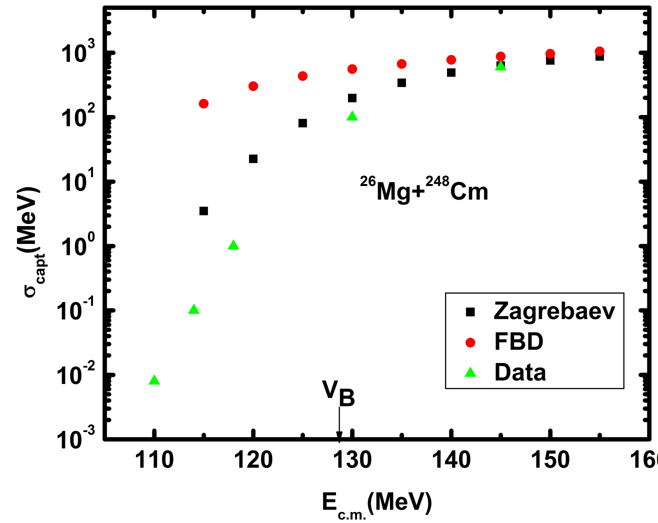
# Models for capture cross sections

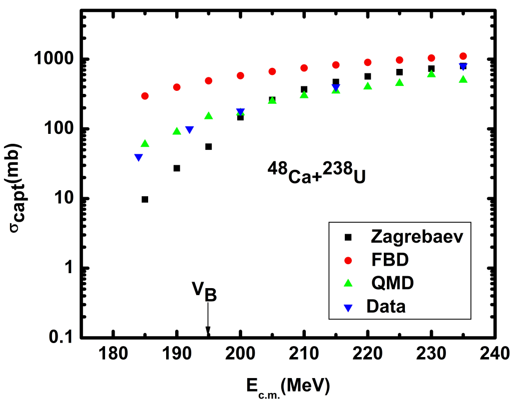
- Improved isospin dependent QMD model (Bian, et al, NPA 829, 1 (2009))
- Modified semi-empirical Swiatecki et al model (PRC 74, 014602 (2005), K. Siwek-Wilczynska, 2009))
- Coupled channels calculations, such as those at http://nrv.jinr.ru/nrv/
- Skyrme energy density functional approach (PRC 74 044604)
- DNS model

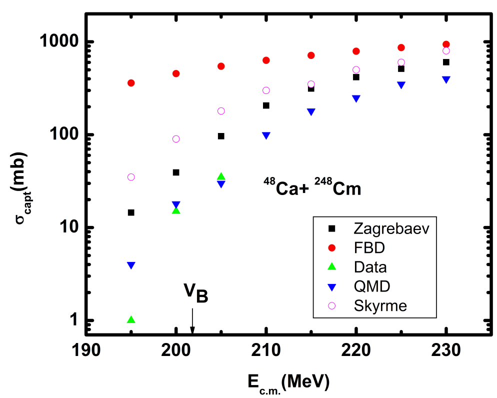
# How successful are the models?

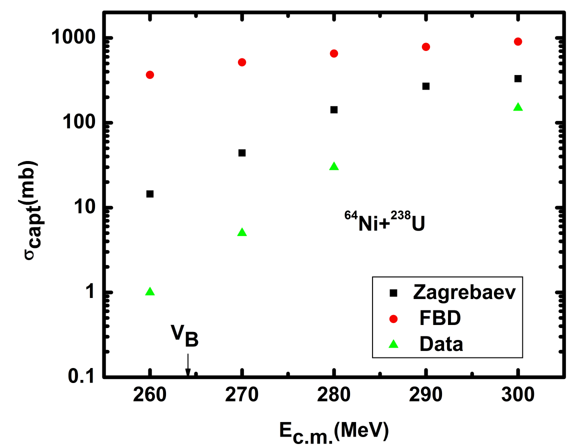


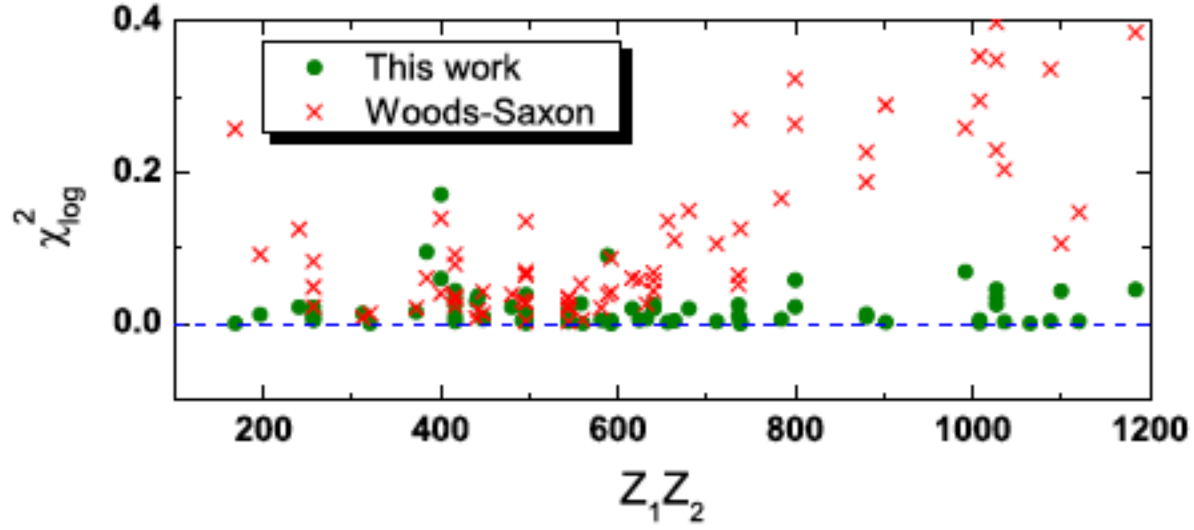



# Aside on DFT methods

For 76 fusion reactions, define

$$\chi^2_{\log} = \frac{1}{m}\sum_{n=1}^{m}[\log(\sigma_{\rm th}(E_n)) - \log(\sigma_{\rm exp}(E_n))]^2.$$



# Conclusions

- For the 50-150 “calibration” reactions, we know capture cross sections within 50%
- We know interaction barriers within 20%
- For the heavy element synthesis reactions, we know the capture cross sections within a factor of 2.

# What about $W_{sur}$?

- Well-established formalism for calculations
- Principal uncertainty is the values of the fission barrier heights.
- Best calculations for SHE fission barrier heights show an average discrepancy between data and theory to be 0.4 MeV, with largest error being 1.0 MeV.

# Calculation of $W_{sur}$

$$W_{sur} = P_{xn}(E^*) \prod_{i=1}^{i_{\max}=x} \left( \frac{\Gamma_n}{\Gamma_n + \Gamma_f} \right)_{i,E^*}$$

**$\Gamma_n/\Gamma_f$ evaluated from Vandenbosch and Huizenga expression**

$$\frac{\Gamma_n(E^*_{CN})}{\Gamma_f(E^*_{CN})} = \frac{4A^{2/3}(E^*_{CN} - B_n)}{k\left\{2a^{1/2}\left(E^*_{CN} - B_f\right)^{1/2} - 1\right\}} \exp(2a^{1/2}\left\{\left(E^*_{CN} - B_n\right)^{1/2} - \left(E^*_{CN} - B_f\right)^{1/2}\right\})$$

**k=9.8 MeV     a=A/12 $MeV^{-1}$**

**$B_n$, $B_f$ from Möller et al., (ADNDT 39,213; 59, 185)**

$$a = \tilde{a}\left[1 + \delta E \frac{1 - \exp(-\gamma E)}{E}\right]$$
$$\gamma = 0.061$$

Collective enhancement of the level density
Deformation dependence of the collective enhancement
Energy dependence of the collective enhancement

# A typical case, $^{274}$Hs

- In the reaction $^{26}$Mg + $^{248}$Cm, we detect neutrons from the decay chain

$$^{274}\mathrm{Hs} \rightarrow {}^{273}\mathrm{Hs} \rightarrow {}^{272}\mathrm{Hs} \rightarrow {}^{271}\mathrm{Hs} \rightarrow {}^{270}\mathrm{Hs} \rightarrow {}^{269}\mathrm{Hs} \rightarrow {}^{268}\mathrm{Hs}$$

$$E^*(\mathrm{MeV}) = 63 \rightarrow 53 \rightarrow 45 \rightarrow 36 \rightarrow 27 \rightarrow 17 \rightarrow 9$$

- For the $^{25}$Mg + $^{248}$Cm reaction, the bombarding energy is chosen such that its decay chain

$$^{273}\mathrm{Hs} \rightarrow {}^{272}\mathrm{Hs} \rightarrow {}^{271}\mathrm{Hs} \rightarrow {}^{270}\mathrm{Hs} \rightarrow {}^{269}\mathrm{Hs} \rightarrow {}^{268}\mathrm{Hs}$$

$$E^*(\mathrm{MeV}) = 53 \rightarrow 45 \rightarrow 36 \rightarrow 27 \rightarrow 17 \rightarrow 9$$

- We do a Harding-Farley experiment fitting the neutron angular and energy distributions to extract pre- and post-fission neutron multiplicities

$$\left(\frac{\Gamma_n}{\Gamma_{tot}}\right)_1 = \frac{{}^{274}\upsilon_{pre}}{1+{}^{273}\upsilon_{pre}}$$

# Continued

- We measure $\left(\frac{\Gamma_n}{\Gamma_{tot}}\right)_1 = 0.89$

This implies dissipative effects ala Kramers.

$$\Gamma_f = \Gamma_f^{BW}(\sqrt{1-x^2} - x) \times \hbar\omega_B/T,$$
$$x = \eta/2\omega_0$$

where $\Gamma_f$ is the corrected fission width, $\Gamma_f^{BW}$ is the standard statistical model width for fission, $x$ is the dimensionless dissipation coefficient where $x = \eta/2\omega_0$, where $\eta$ is the nuclear viscosity, and $\omega_0$ and $\omega_B$ are the characteristic frequencies of parabolic approximations of the nuclear potential energy near the ground state and the saddle point. $B_f$ is the fission barrier

What are our choices about fission barrier heights for this system?

| | |
|---|---|
| Kowal, et al. (PRC 82, 014303) | 4.37 MeV |
| ETFSI | 2.50 |
| FRLDM | 5.31 |

# How well can we calculate $W_{sur}$?

- We took a group (~75 ) heavy element synthesis reactions where $Z_1Z_2 < 1000$ ($Z_{CN}$ =98-108) and compared the calculated and measured values of $\sigma_{EVR}$.
- The average ratio of (measured/ calculated) cross sections was 6.5. We conclude that we know $W_{sur}$ within a factor of 3.

# What about $P_{CN}$?

- This is the most difficult quantity to estimate or measure.
- There are a limited number of measurements of $P_{CN}$.

# How do you measure $P_{CN}$?

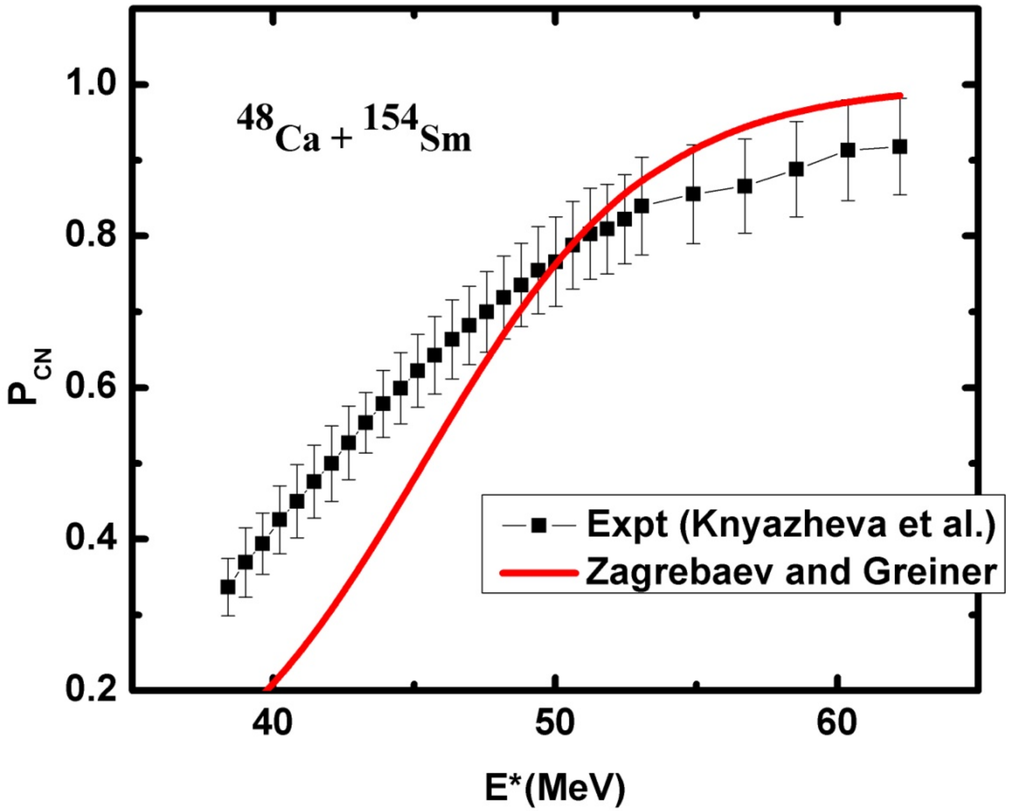
- Angular distribution method (Back)
- Fusion-fission is assumed to be described by the ordinary transition state model of fission angular distributions while quasifission is described by a strongly fore-aft peaked distribution.

# Excitation Energy Dependence of $P_{CN}$

Zagrebaev and Greiner

$$P_{CN}(E^*, J) = \frac{P_{CN}^0}{1 + \exp\left[\frac{E_B^* - E_{\text{int}}^*(J)}{\Delta}\right]}$$

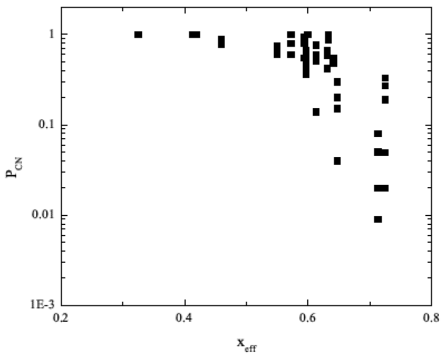
# $P_{CN}$ (E*)



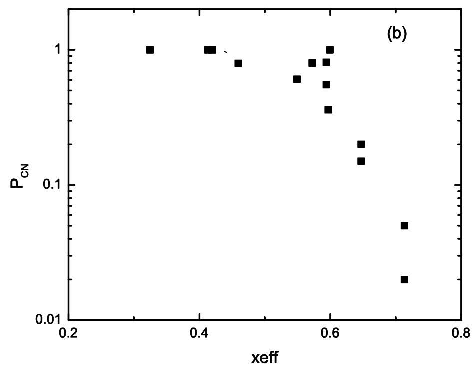
1.0
0.8
0.6
0.4
0.2
$P_{CN}$
40
50
60
E*(MeV)
$^{48}$Ca + $^{154}$Sm
Expt (Knyazheva et al.)
Zagrebaev and Greiner

# $P_{CN}$ dependence on fissility

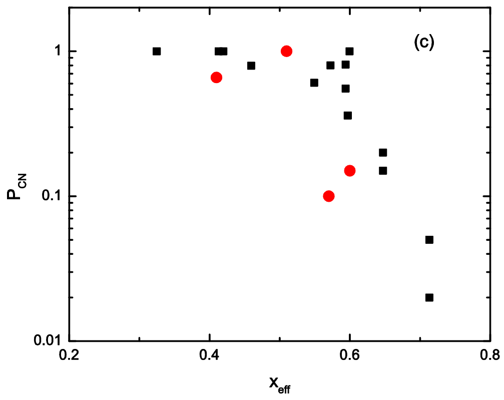
All data



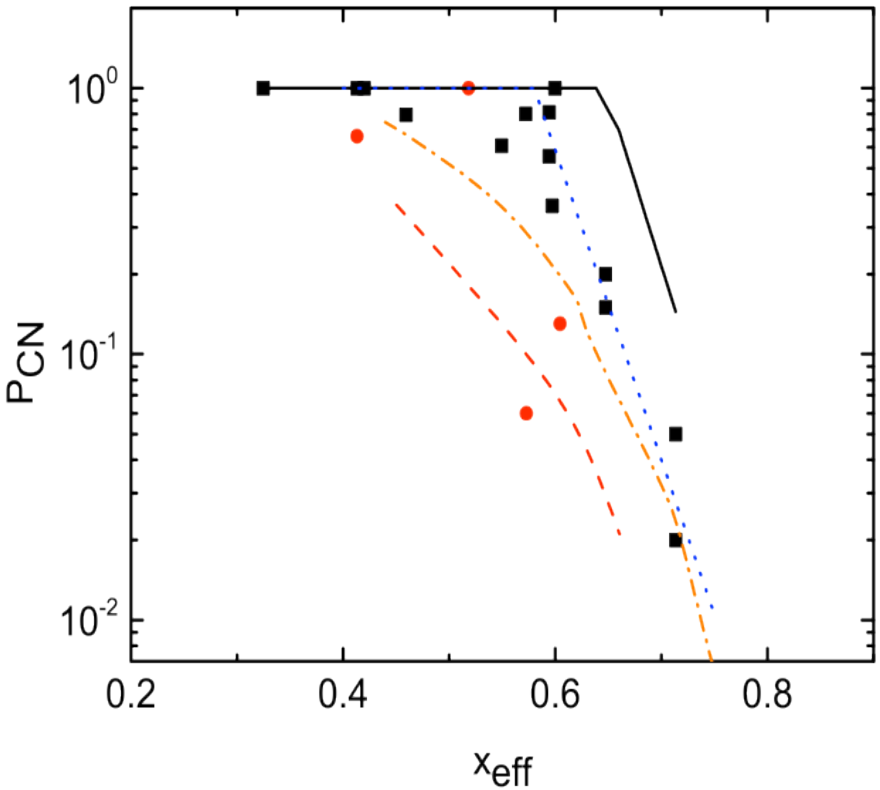

E*=40-50 MeV




New data



# Models for $P_{CN}$




Solid line, Z-G, dashed line FBD, dot-dash Int.J.Mod Phys.E 17,12,
Dotted line is fit

# What do we do now?

- Wait for TDHF?
- What does TDHF mean?
- What do we (experimentalists) use in our “tool” kits?

# "Scission" neutrons

- In spontaneous and thermal neutron induced fission, one might expect all of the prompt fission neutrons to be emitted from the fully accelerated fission fragments.
- Since 1962, a controversy has raged (in both theory and experiments) about the possibility of some fraction (perhaps as much as 30%) of the prompt neutrons which are emitted isotropically.

# History

- 1962 (Bowman, Thompson, Milton, Swiatecki, PR 126, 2120) Scission neuts are ~ 10% of all neuts in $^{252}Cf$ sp. f.
- 1963 (Kapoor, et al., PR 131, 283) Scission neuts are ~ 10% of all neuts in $^{235}U(n_{th}, f)$
- 1988 (Budtz-Jorgenson and Knitter, NPA, 490, 307) Scission neuts "negligible" in $^{252}Cf$ sp. f.
- 1992 (Brosa and Knitter) Scission neuts are ~ 1.1% of neuts in $^{252}Cf$.
- 1999 (Hwang et al., PRC, 60, 044616) Scission neuts (2 n emission) are 0.06% of $^{252}Cf$ neuts.

# History (cont.)

- 2001 (Kornilov et al., NPA 686, 187) In $^{252}$Cf sp. f , 30 ± 5 % of prompt neutrons are scission neuts.
- 2009 Petrov et al., AIP Conference Proc. 1175, 289) Comprehensive expt'l study says scission neuts are 10 ± 2, 5 ± 2, 7± 2, and 10 ±2 % of all prompt neutrons in $^{252}$Cf, $^{233}$U($n_{th}$,f), $^{235}$U($n_{th}$,f) and $^{239}$Pu ($n_{th}$, f), respectively.

# Theory

- 2010 Carjan and Rizea, PRC 82, 014617 Scission neuts represent up to 30% of all prompt neuts in $^{235}U(n_{th},f)$
- 2013 Wada et al. (Physics Procedia, 47, 33) Signature of scission neuts is not isotropy, due to re-absorption and scattering by fragments

# Summary

- It is “disturbing” , “surprising” etc. to think that 70+ years since the discovery of fission, we still don’t understand the origin of as many as 10+ % of the prompt neutrons.
- These scission neutrons contribute to the poorly known lower energy portion of the spectrum of the emitted neutrons.
- The neutron multiplicities and spectra have and will be measured correctly but we need guidance on how to interpret the observations.