

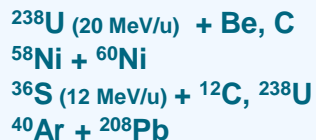
## 1. Fission barrier dialog modification

## 2. Fusion dialogs

- ❖ *Potential energy*
- ❖ *Potential pocket,  $L_{critical}$ , DIC*
- ❖ *Fission barrier vanishing,  $L_{Bfis=0}$ , Fast Fission (FA)*
- ❖ *Compound Formation, Quasi-Fission*
- ❖ *Barrier penetration, Quasi-Elastic (QE)*
- ❖ *Compound de-excitation : Fusion – Fission or Residue?*

## 3. LISE<sup>++</sup> definitions and features of fusion mechanism

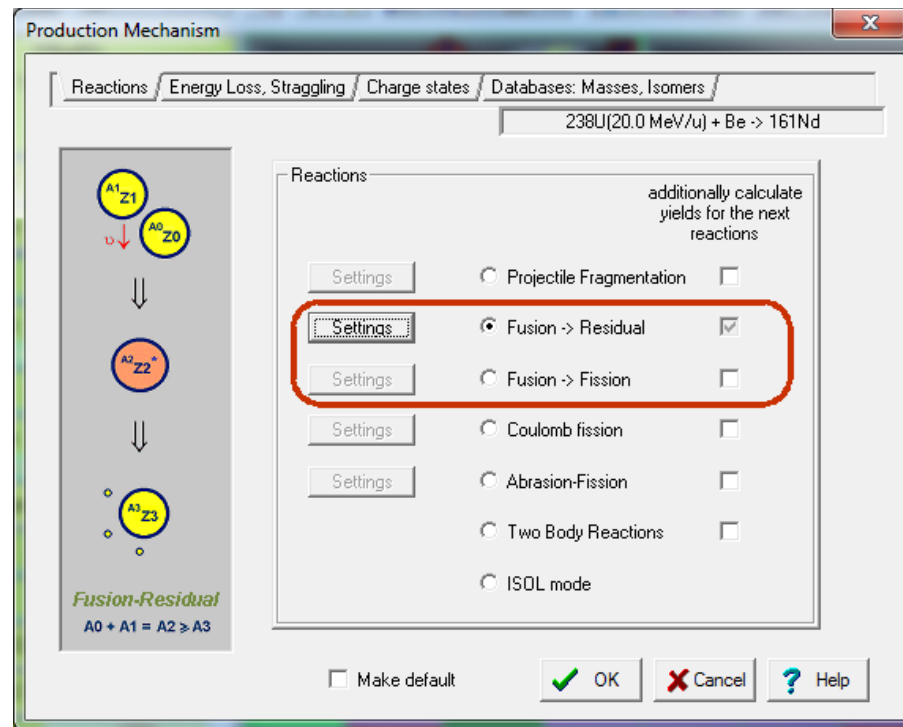
## 4. Examples:



**v.9.10.60**  
from 04/09/15

### Purpose:

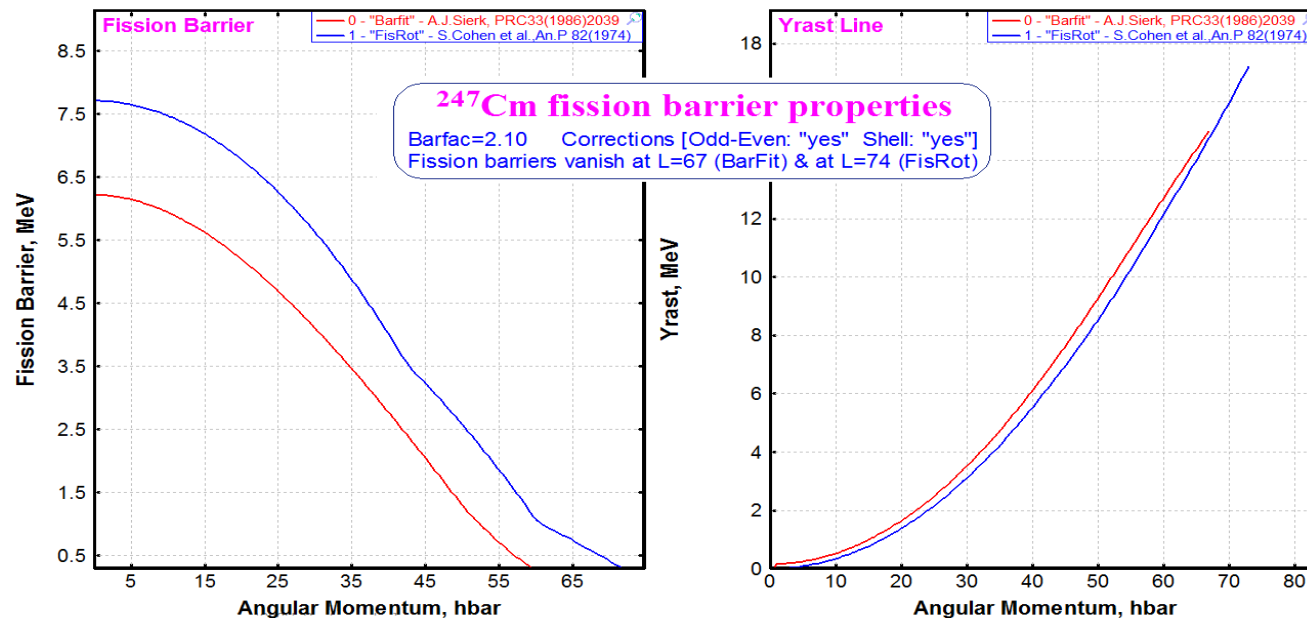
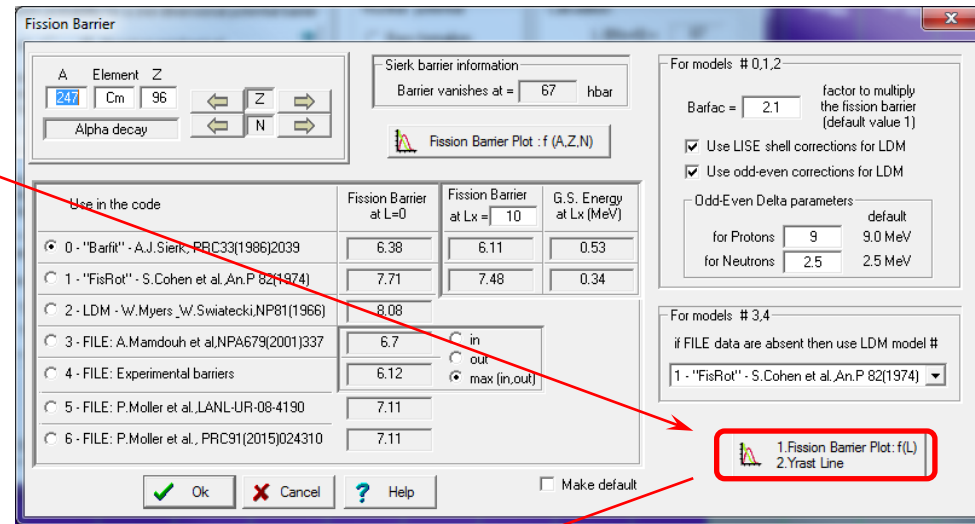
*implementation of angular momentum formalism into low-energy reactions*



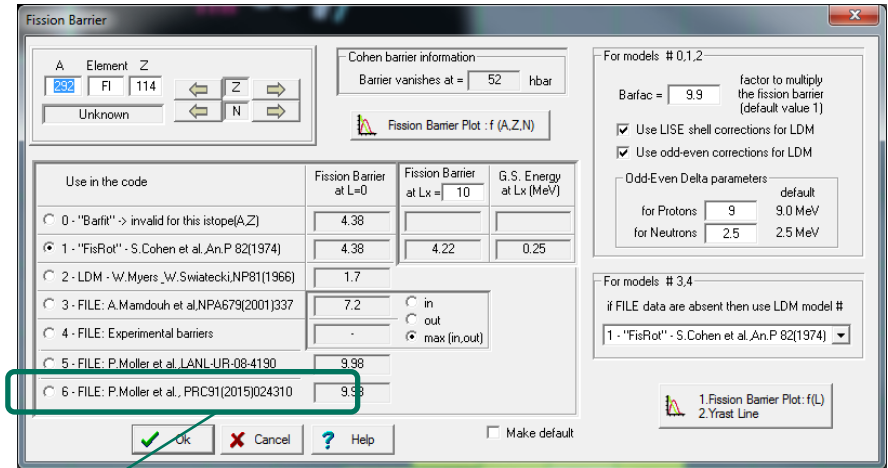
LISE<sup>++</sup> documentation:

- [Fusion residue transmission v.5.15](#)
- [Fusion-Fission v.7.8](#)
- [Angular momenta vs reaction channels](#)

1. Fission barrier and Yrast line plots as function of L
2. New Fission barriers from P.Moller et al., PRC91(2015)024310
3. BarFac parameter for the SHE region
4. Sierk's fission barrier validity

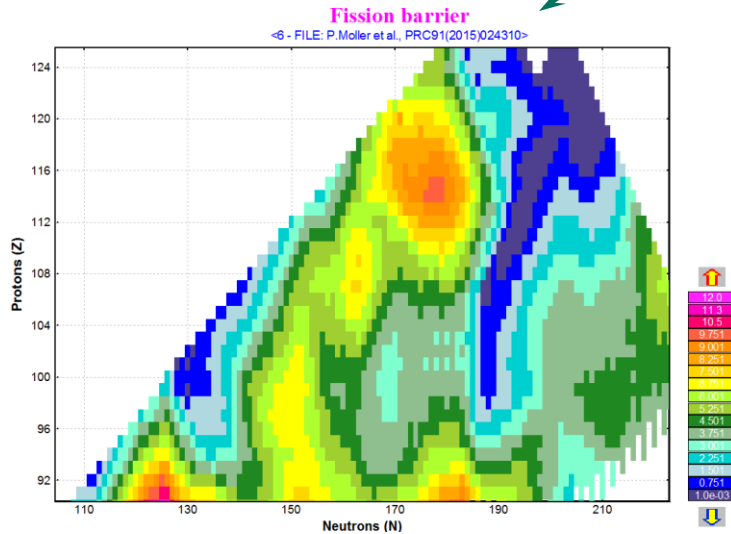


1. Fission barrier and Yrast line plots as function of L
2. **New Fission barriers from P.Moller et al., PRC91(2015)024310**
3. BarFac parameter for the SHE region
4. Sierk's fission barrier validity

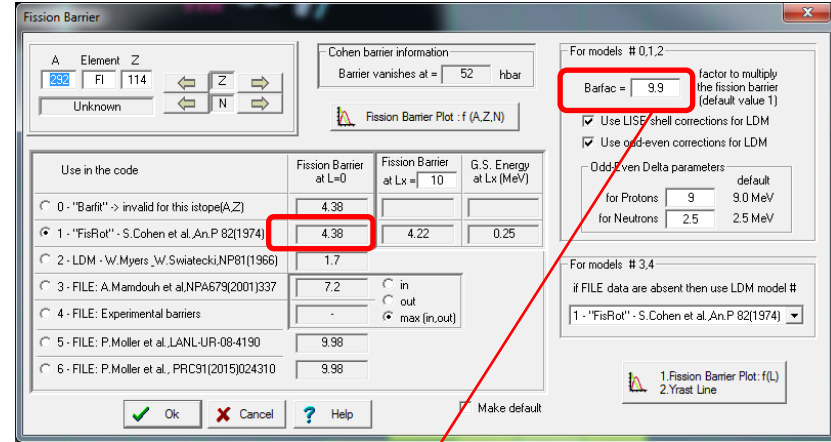


It looks like a high Barrier value with AME2012 use.

But LISE++ allows to load a user mass excess table

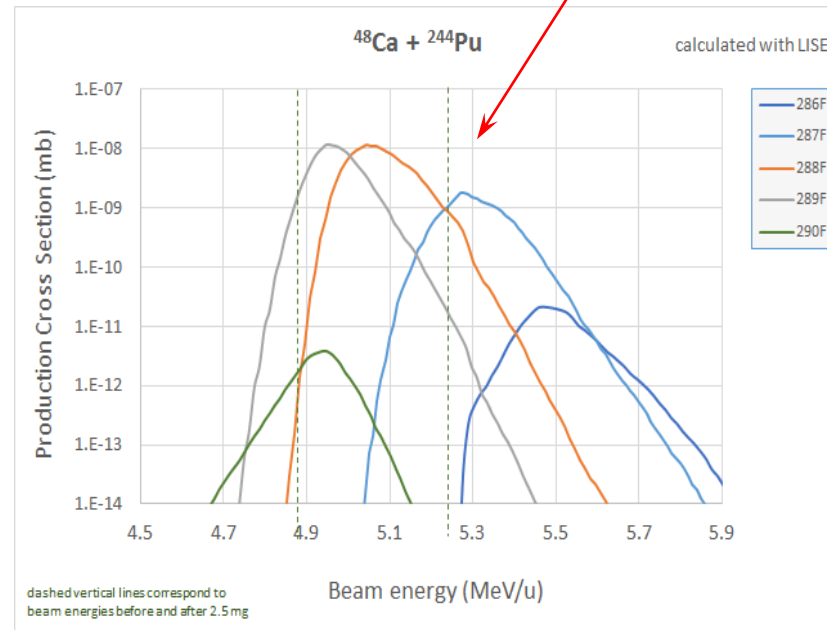


1. Fission barrier and Yrast line plots as function of L
2. New Fission barriers from P.Moller et al., PRC91(2015)024310
3. BarFac parameter for the SHE region
4. Sierk's fission barrier validity



Barrier factor to describe experimental data or sophisticated calculations

Fission barrier value plays crucial role between particle evaporation and fission competition in de-excitation process



1. Fission barrier and Yrast line plots as function of  $L$
  2. New Fission barriers from P.Moller et al., PRC91(2015)024310
  3. BarFac parameter for the SHE region
  4. **Sierck's fission barrier validity**
0. Sierck's fission barrier is operating up to  $Z \leq 110 @ L=0$  or  $Z \leq 102 @ L>0$
  1. So, if Sierck's fission barrier has been selected, and nucleus atomic number is higher 110 at  $L=0$ , than Cohen's barrier will be used.
  2. If if Sierck's fission barrier has been selected, and nucleus atomic number is higher 102 at  $L>0$ , then vanishing factor for  $Z=102$  (with the same  $N/Z$  ratio) will be used,

Vanishing barrier factor for data from FILEs is based on selection from Sierck or Cohen models in the Fusion dialog

where the Vanishing factor ( $L$ ) is the ratio of  $\text{Barrier}(A,Z,L) / \text{Barrier}(A,Z,0)$

Fission barrier vanishing

Take into account the Fission barrier vanishing with

0 - "Barfit" - A.J.Sierck, PRC33(1986)2039

1 - "FisRot" - S.Cohen et al.,An.P 82(1974)

$$\sigma_{ER}^{xn}(E) = \frac{\pi}{k^2} \sum_{l=0}^{\infty} (2l + 1) P_{\text{cont}}(E, l) P_{\text{CN}}(E^*, l) P_{xn}(E^*, l)$$

The screenshot shows the 'Fusion -> Fission' dialog box with the following settings:

- Evaporation settings:** 238U(24.0 MeV/u) + 9Be -> 247Cm\* (Ex=201.5MeV)
- Fusion properties:**
  - Transmission probability for a one-dimensional potential barrier:  Classical,  Quantum-mechanical
  - h\_omega - Curvature parameter of the parabolic potential describing the barrier (default value 3 MeV): 5 MeV
  - Probability for compound nucleus formation P\_{CN}:  Take into account the Probability for compound nucleus formation P\_{CN} according to V.Zagrebaev & W.Greiner, PRC78, 034610 (2008)
  - Fission barrier vanishing:  Take into account the Fission barrier vanishing with:
    - 0 - "Barfit" - A.J.Sierk, PRC33(1986)2039
    - 1 - "FisRot" - S.Cohen et al. An.P 82(1974)
- Nuclear potential:**
  - Bass formalism
  - Wood-Saxon
  - V0 = 105 MeV
  - R0 = 1.12 fm
  - a = 0.75 fm
  - Fusion L-diffuseness: 1 MeV
- Calculation:**
  - L (Bfis=0) = 67
  - L critical = 75
  - L direct (@ Rint) = 85
  - L max (grazing) = 99.9
  - L max (LISE) = 100.3
  - Show Details & CS:
- Partner site:**
  - 
  -

**Do not hesitate to use Low-Energy reaction computing centers as NRV for more sophisticated solutions with Channel Coupling, Langevin equations and so on**

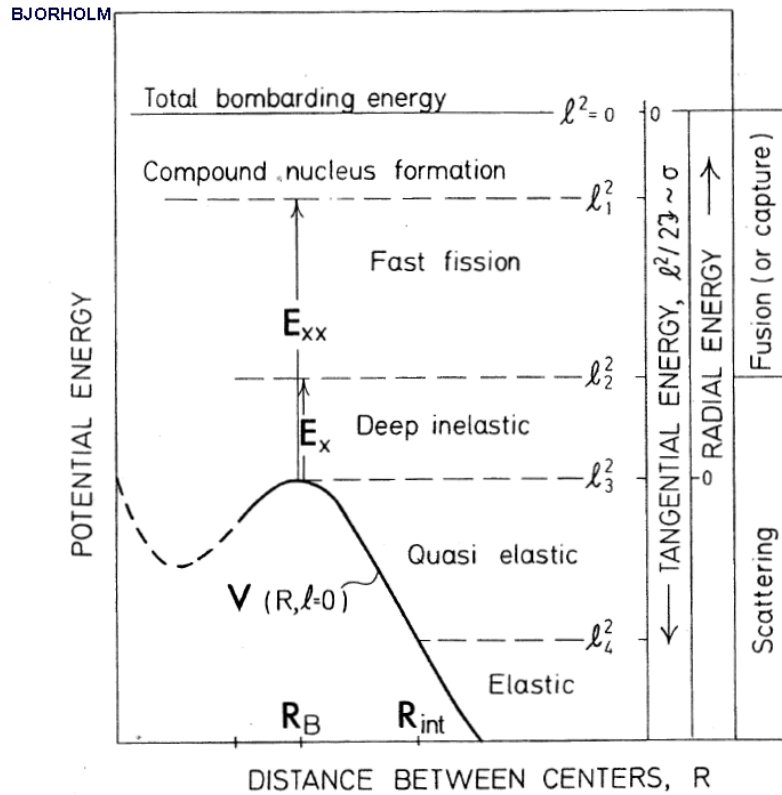


Fig. 5. Summary of the different reactions encountered in collisions between very heavy ions

C.Gregoire et al.

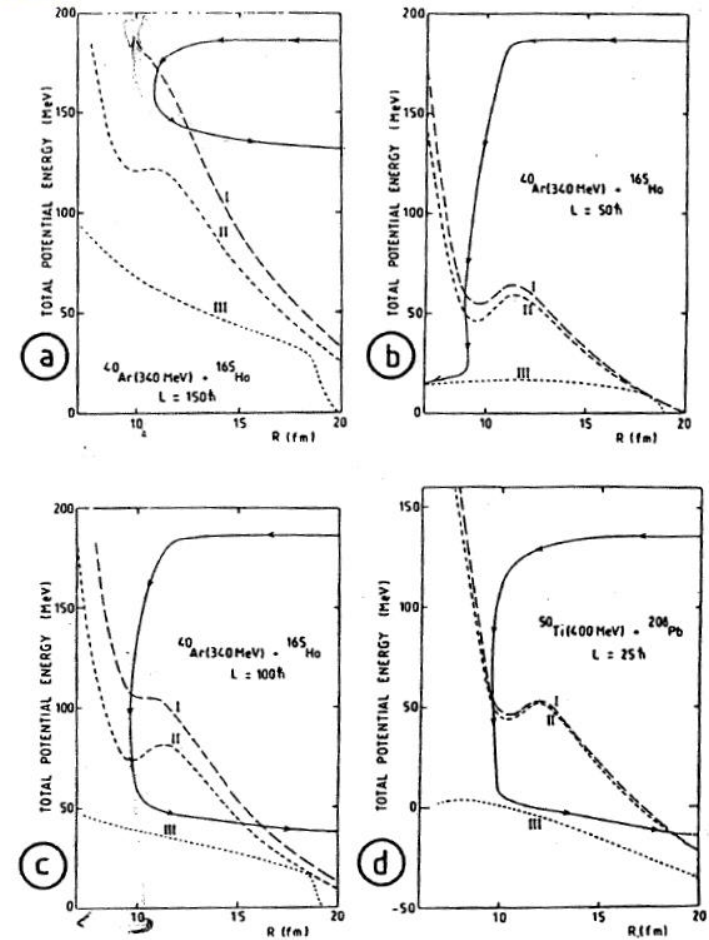


Fig. 3 - Dissipative processes in heavy ion reactions :  
 a) deep inelastic collisions,  
 b) compound nucleus formation,  
 c) fast fission,  
 d) fast fission with very heavy systems or quasi fission.

$$V(l, r) = V_{\text{nuci}}(r) + V_{\text{Coul}}(r) + l(l + 1)\hbar^2/2\mu r^2$$

$$V_{\text{nuc}}(r) = -V_0\{1 + \exp[(r - r_0(A_P^{1/3} + A_T^{1/3}))/a])\}^{-1}$$

Default NRV parameters

Nuclear potential

Bass formalism

Wood-Saxon

V0 = 105 MeV

R0 = 1.12 fm

a = 0.75 fm

Fusion L-diffuseness 1 MeV

Partial Cross Sections

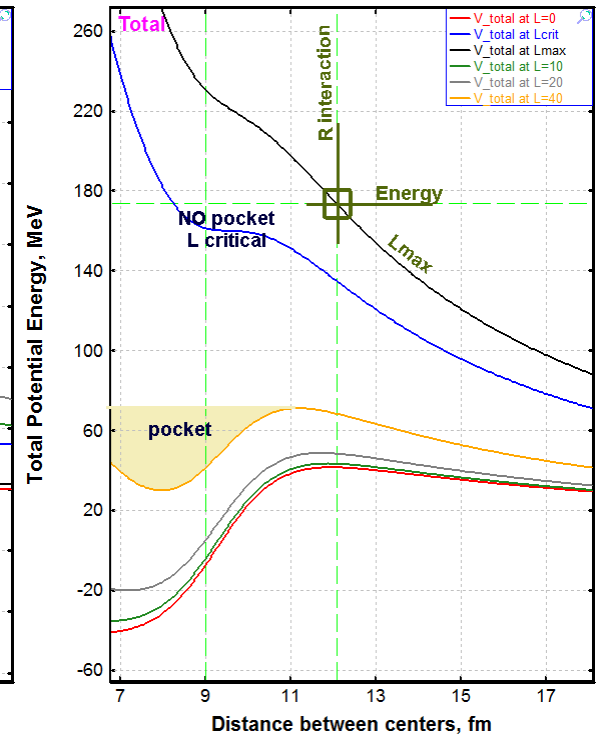
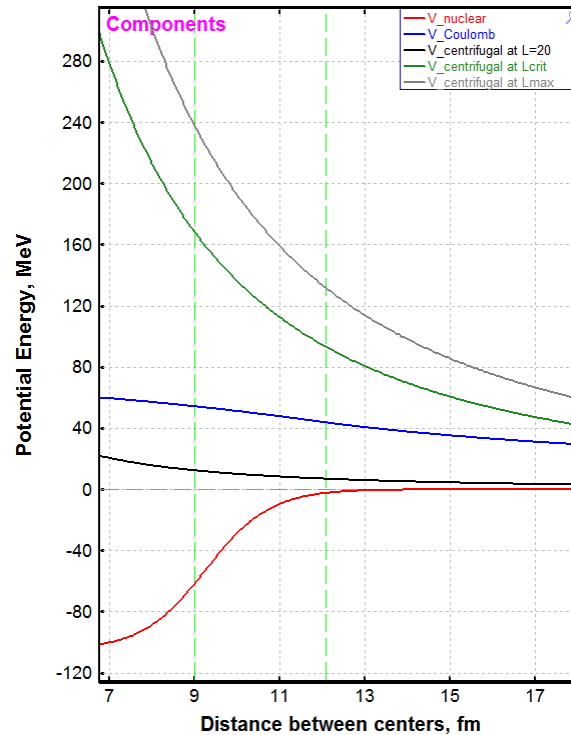
Potentials  $V_i = f(R)$

T, PCN, dEx-chan as f(L)

## Potential energy plot

$^{238}\text{U}(20.0 \text{ MeV/u}) + ^9\text{Be} \rightarrow ^{247}\text{Cm}^*$  ( $E_{\text{CM}}=173.6 \text{ MeV}$ )

$L_{\text{crit}}=75$ ;  $L_{\text{max}}^{\text{Graz}}=88.7$ ;  $L_{\text{max}}^{\text{LISE}}=89.2$ ; Nuclear potential: WoodSaxon; WS params: 105.0,1.12,0.75  
 Vertical lines correspond to  $(C_p + C_t)$  and  $R_{\text{interaction}}$ , Right horizontal line to  $E_{\text{CM}}$





Critical momentum : L-value corresponds to potential energy when the pocket is washed out. No fusion

Calculation

L (Bfis=0) = 67

**L critical = 75**

L direct (@ Rint) = 78

L max (grazing) = 88.7

L max (LISE) = 89.2

Show Details & CS ?

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Barrier properties as f(L)

Bass Fusion CS & Barrier

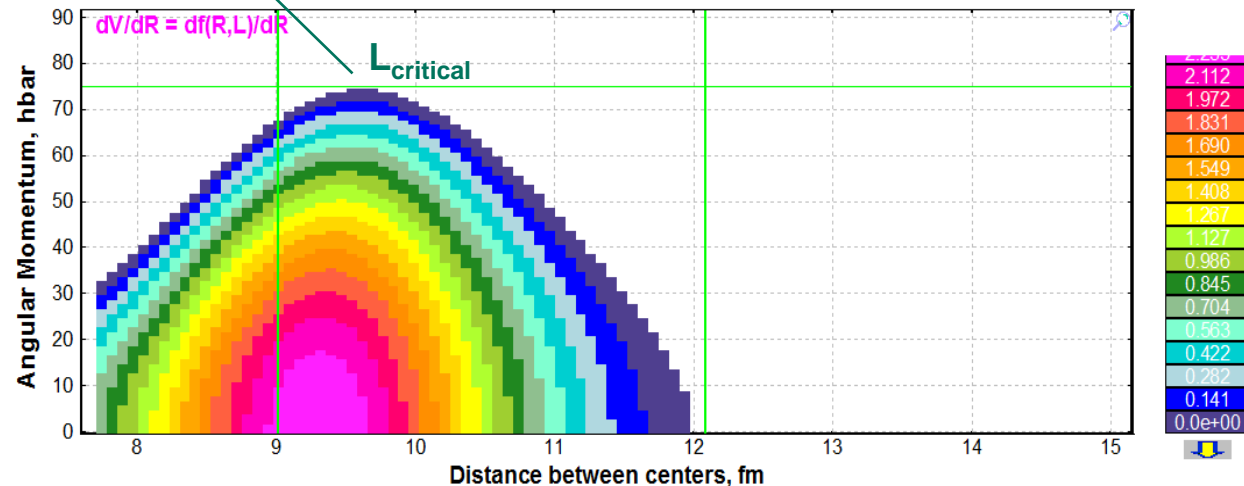
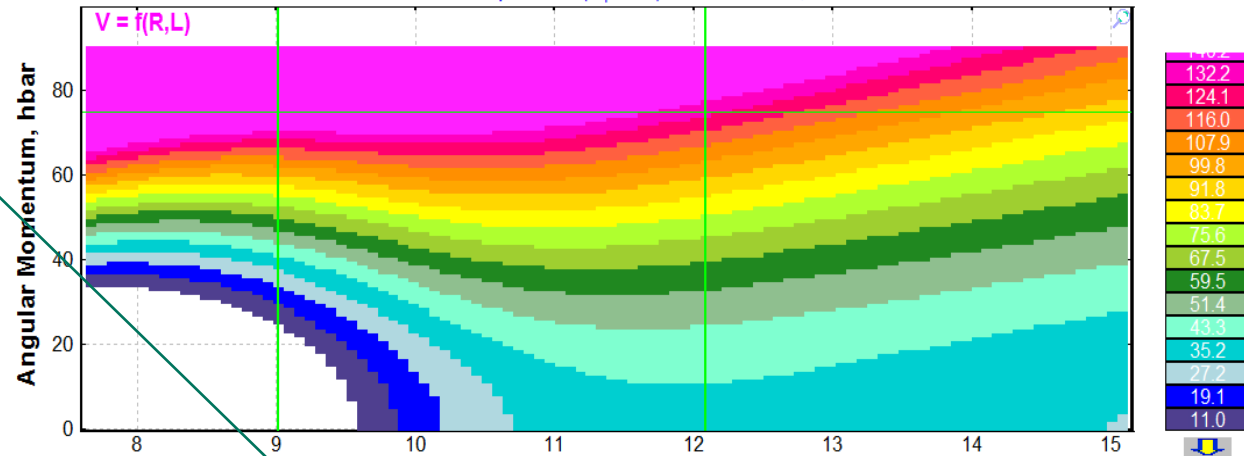
**2D: Barrier V=f(R,L) & dV/dR**

## 2D Potential plots as $f(R,L)$ & $df(R,L)/dR$



$L_{\text{crit}}=75$ ;  $L_{\text{max}}^{\text{Graz}}=88.7$ ;  $L_{\text{max}}^{\text{LISE}}=89.2$ ; Nuclear potential: WoodSaxon; WS params: 105.0,1.12,0.75

Vertical lines correspond to  $(C_p + C_t)$  and  $R_{\text{interaction}}$ , Horizontal line to  $L_{\text{critical}}$



**Deep Inelastic Collision region**  
 $L_{\text{critical}} \leq L < L_{\text{direct}}$

The potential pocket does not exist, and the Energy<sub>CM</sub> is above the barrier

Calculation

L (Bfis=0) = 67

L critical = 75

L direct (@ Rint) = 78

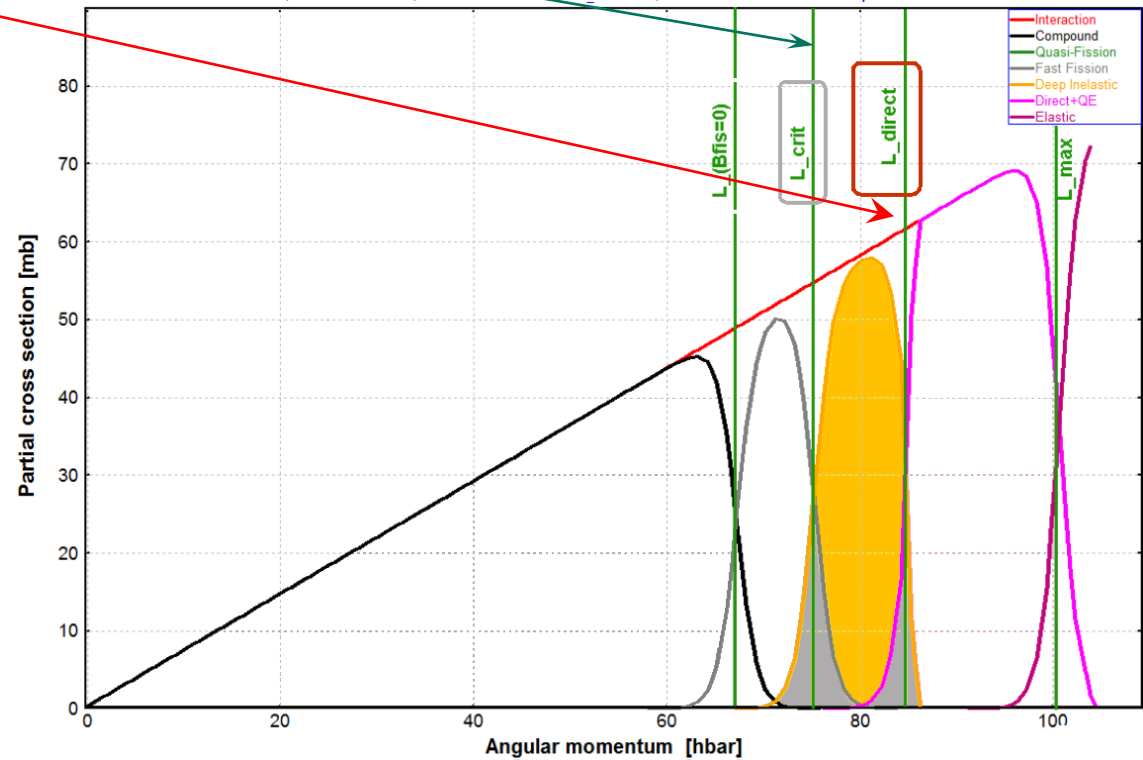
L max (grazing) = 88.7

L max (LISE) = 89.2

Show Details & CS ?

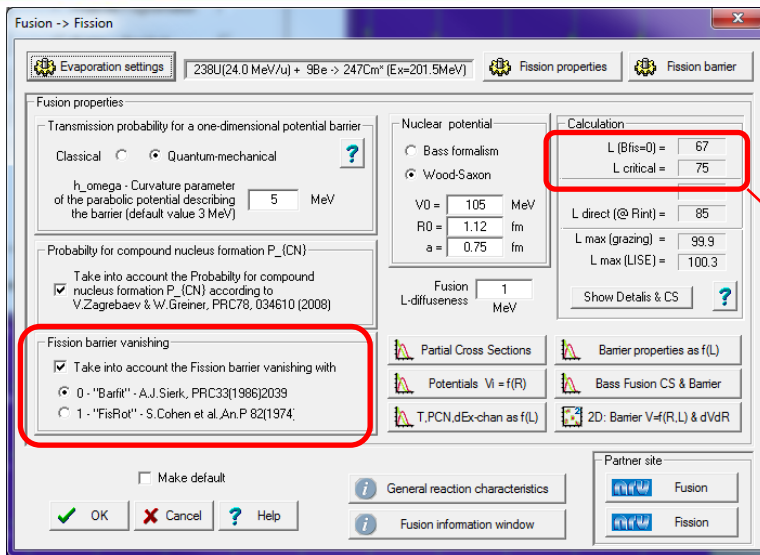
## Partial cross sections

$^{238}\text{U}(24.0 \text{ MeV/u}) + ^9\text{Be} \rightarrow ^{247}\text{Cm}^* (E_{\text{CM}}=208.3 \text{ MeV});$  [with  $P_{\text{CN}}$ , Penetration $^{Q,M}$ ]  
 Cross Sections[mb]: Int=3.69e+03; Comp=1.66e+03; QF=1.54e-07; FA=4.16e+02; DIC=5.36e+02; QE=1.08e+03;  
 $L_{\text{crit}}=75; L_{\text{max}}^{\text{Graz}}=99.9; L_{\text{max}}^{\text{LISE}}=100.3; L_{\text{B-fis}}=67;$  Vertical lines correspond to  $L_{\text{crit}}$  &  $L_{\text{max}}$



**Deep Inelastic Collision region**  
 $L_{\text{critical}} \leq L < L_{\text{direct}}$

The potential pocket does not exist, and the Energy<sub>CM</sub> is above the barrier

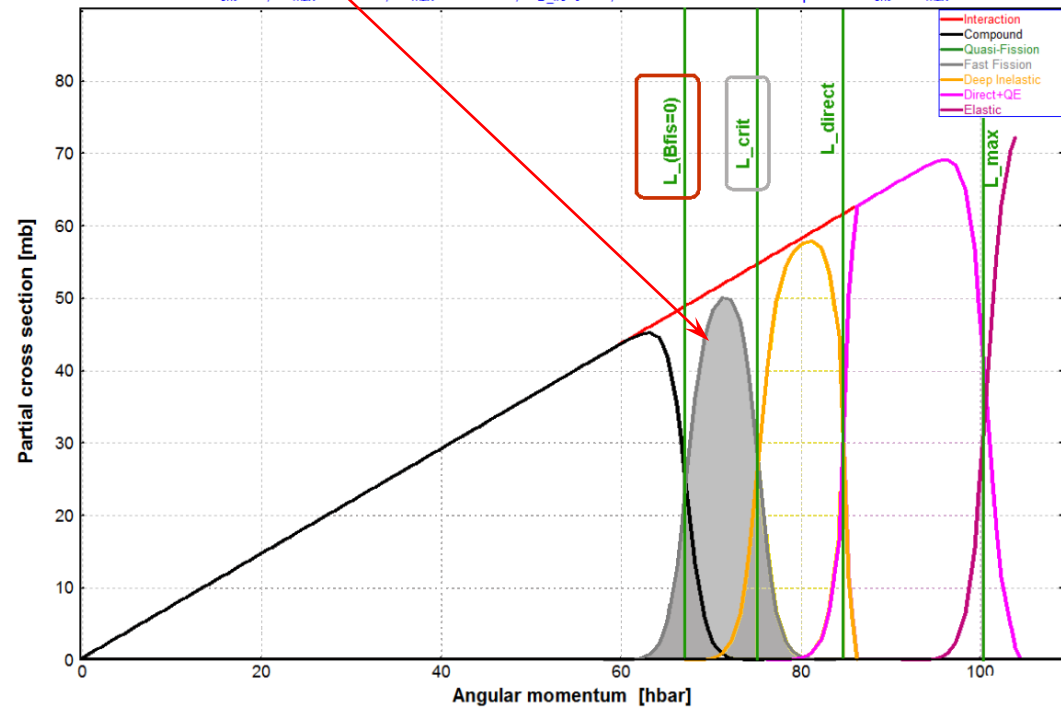


**Fast Fission region**

$$L_{Bfis=0} \leq L < L_{critical}$$

**Partial cross sections**

$^{238}\text{U}(24.0 \text{ MeV/u}) + ^9\text{Be} \rightarrow ^{247}\text{Cm}^* (E_{CM}=208.3 \text{ MeV})$ ; [with  $P_{CN}$ , Penetration $^{Q,M}$ ]  
 Cross Sections[mb]: Int=3.69e+03; Comp=1.66e+03; QF=1.54e-07; FA=4.16e+02; DIC=5.36e+02; QE=1.08e+03;  
 $L_{crit}=75$ ;  $L_{max}^{Gras}=99.9$ ;  $L_{max}^{LISE}=100.3$ ;  $L_{Bfis=0}=67$ ; Vertical lines correspond to  $L_{crit}$  &  $L_{max}$



**The potential pocket still exists, but no compound formation**

Fusion -> Residues

Evaporation settings:  $^{48}\text{Ca}(6.0 \text{ MeV/u}) + ^{208}\text{Pb} \rightarrow ^{256}\text{No}^* [E_x=79.8 \text{ MeV}]$

Fusion properties

Transmission probability for a one-dimensional potential barrier

Classical  Quantum-mechanical

$h_\omega$  - Curvature parameter of the parabolic potential describing the barrier (default value 3 MeV)  MeV

Probability for compound nucleus formation  $P_{\text{CN}}$

Take into account the Probability for compound nucleus formation  $P_{\text{CN}}$  according to V.Zagrebaev & W.Greiner, PRC78, 034610 (2008)

Fission barrier vanishing

Take into account the Fission barrier vanishing with

0 - "Barfi" - A.J.Sierk, PRC33(1986)2039

1 - "FisRot" - S.Cohen et al., An.P 82(1974)

Nuclear potential

Bass formalism

Wood-Saxon

$V_0 = 105$  MeV

$R_0 = 1.12$  fm

$a = 0.75$  fm

Fusion L-diffuseness  MeV

Partial Cross Sections

Potentials  $V_i = f(R)$

T, PCN, dEx-chan as f(L)

PHYSICAL REVIEW C 78, 034610 (2008)

## Synthesis of superheavy nuclei: A search for new production reactions

Valery Zagrebaev<sup>1</sup> and Walter Greiner<sup>2</sup>

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

$$P_{\text{CN}}^0 = \frac{1}{1 + \exp\left[\frac{Z_1 Z_2 - \zeta}{\tau}\right]}$$

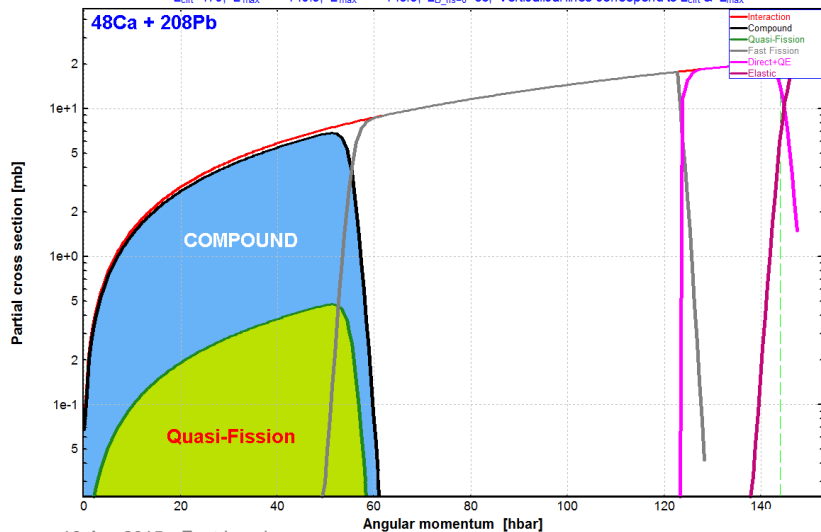
FIG. 5. Above-barrier CN formation probability in the  $^{208}\text{Pb}$  induced fusion reactions. Results of calculation are shown by the circles, whereas the fitted curve corresponds to expression (3).

### Partial cross sections

$^{48}\text{Ca}(6.0 \text{ MeV/u}) + ^{208}\text{Pb} \rightarrow ^{256}\text{No}^* (E_{\text{CM}}=233.6 \text{ MeV})$ ; [with  $P_{\text{CN}}$ , Penetration<sup>Q 10</sup>]

Cross Sections [mb]: Int=1.51e+03; Comp=2.08e+02; QF=1.45e+01; FA=8.80e+02; QE=4.03e+02;

$L_{\text{crit}}=170$ ;  $L_{\text{max}}^{\text{Graz}}=140.9$ ;  $L_{\text{max}}^{\text{LISE}}=143.9$ ;  $L_{\text{B, fis}=0}=55$ ; Vertical lines correspond to  $L_{\text{crit}}$  &  $L_{\text{max}}$

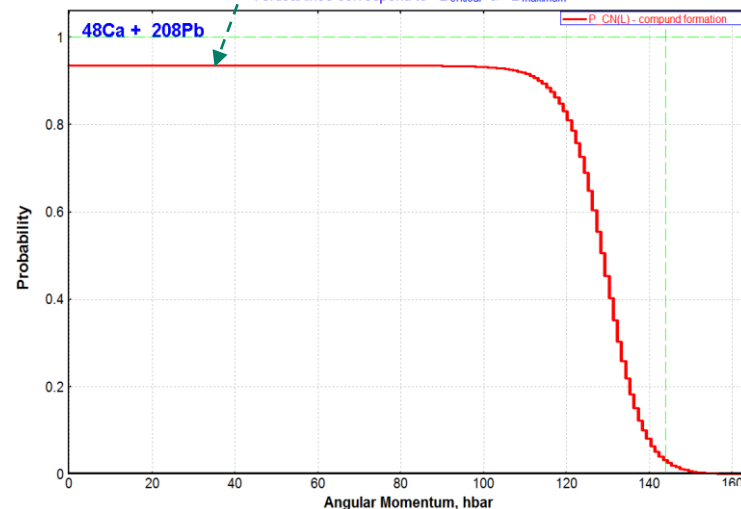


### Probabilities as f(L): $P_{\text{CN}}$ , T(L)

$^{48}\text{Ca}(6.0 \text{ MeV/u}) + ^{208}\text{Pb} \rightarrow ^{256}\text{No}^* (E_{\text{CM}}=233.6 \text{ MeV})$ ;  $h_\omega=5.0$

$L_{\text{crit}}=170$ ;  $L_{\text{max}}^{\text{Graz}}=140.9$ ;  $L_{\text{max}}^{\text{LISE}}=143.9$ ; Nuclear potential: WoodSaxon

Vertical lines correspond to  $L_{\text{critical}}$  &  $L_{\text{maximum}}$



Fusion -> Residues

Evaporation settings:  $^{58}\text{Fe}(6.0 \text{ MeV/u}) + ^{208}\text{Pb} \rightarrow ^{266}\text{Hs}^* (E_x=66.5 \text{ MeV})$

Fusion properties:

Transmission probability for a one-dimensional potential barrier:  
 Classical  Quantum-mechanical  ?  
 $\hbar\omega$  - Curvature parameter of the parabolic potential describing the barrier (default value 3 MeV): 5 MeV

Nuclear potential:  
 Bass formalism  
 Wood-Saxon  
 $V_0 = 105 \text{ MeV}$   
 $R_0 = 1.12 \text{ fm}$   
 $a = 0.75 \text{ fm}$   
 Fusion L-diffuseness: 1 MeV

Probability for compound nucleus formation  $P_{\text{CN}}$ :  
 Take into account the Probability for compound nucleus formation  $P_{\text{CN}}$  according to V.Zagrebaev & W.Greiner, PRC78, 034610 (2008)

Fission barrier vanishing:  
 Take into account the Fission barrier vanishing with:  
 0 - "Barit" - A.J.Sierk, PRC33(1986)2039  
 1 - "FisRot" - S.Cohen et al., An.P 82(1974)

Partial Cross Sections  
 Potentials  $V_i = f(R)$   
 $T, P_{\text{CN}}, dEx\text{-chan as f(L)}$

PHYSICAL REVIEW C 78, 034610 (2008)

## Synthesis of superheavy nuclei: A search for new production reactions

Valery Zagrebaev<sup>1</sup> and Walter Greiner<sup>2</sup>

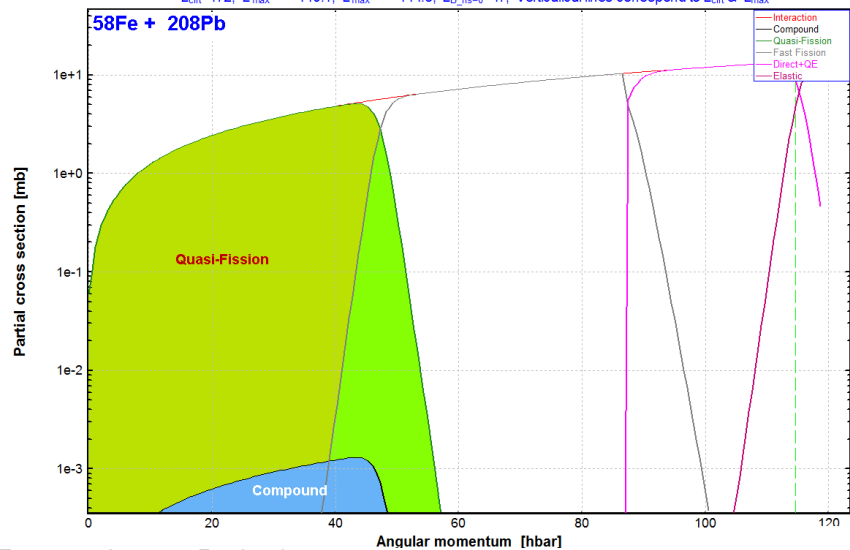
$$P_{\text{CN}}(E^*, l) = \frac{P_{\text{CN}}^0}{1 + \exp\left[\frac{E_B^* - E_{\text{int}}^*(l)}{\Delta}\right]}$$

$$P_{\text{CN}}^0 = \frac{1}{1 + \exp\left[\frac{Z_1 Z_2 - \zeta}{\tau}\right]}$$

FIG. 5. Above-barrier CN formation probability in the  $^{208}\text{Pb}$  induced fusion reactions. Results of calculation are shown by the circles, whereas the fitted curve corresponds to expression (3).

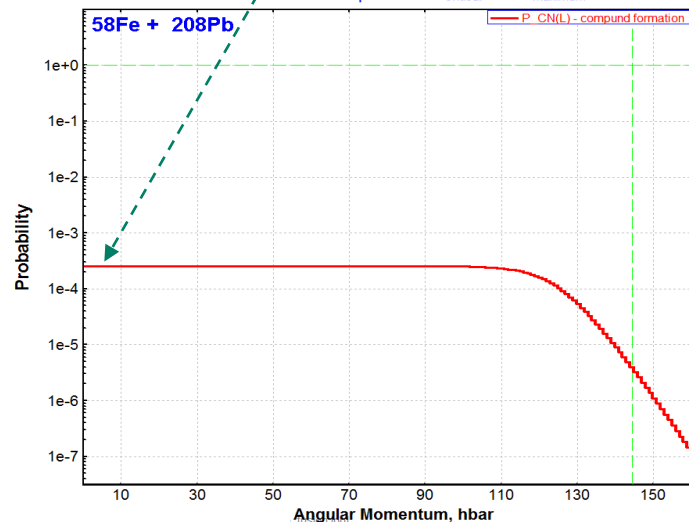
### Partial cross sections

$^{58}\text{Fe}(6.0 \text{ MeV/u}) + ^{208}\text{Pb} \rightarrow ^{266}\text{Hs}^* (E_{\text{CM}}=256.7 \text{ MeV})$ ; [with  $P_{\text{CN}}$ , Penetration<sup>Q.M</sup>]  
 Cross Sections[mb] : Intr=7.92e+02; Comp=3.46e-02; QF=1.35e+02; FA=3.29e+02; QE=3.28e+02;  
 $L_{\text{crit}}=172$ ;  $L_{\text{max}}^{\text{GrZ}}=110.1$ ;  $L_{\text{max}}^{\text{LISE}}=114.6$ ;  $L_{\text{f, fis}=0}=47$ ; Vertical lines correspond to  $L_{\text{crit}}$  &  $L_{\text{max}}$



### Probabilities as f(L): $P_{\text{CN}}$ , $T(L)$

$^{58}\text{Fe}(6.0 \text{ MeV/u}) + ^{208}\text{Pb} \rightarrow ^{266}\text{Hs}^* (E_{\text{CM}}=271.6 \text{ MeV})$ ;  $\hbar\omega=5.0$   
 $L_{\text{crit}}=180$ ;  $L_{\text{max}}^{\text{GrZ}}=140.6$ ;  $L_{\text{max}}^{\text{LISE}}=144.4$ ; Nuclear potential: WoodSaxon  
 Vertical lines correspond to  $L_{\text{critical}}$  &  $L_{\text{maximum}}$



Fusion -> Residues

Evaporation settings:  $^{238}\text{U}(5.4 \text{ MeV/u}) + ^{12}\text{C} \rightarrow ^{250}\text{Cf}^* (E_x=37.8 \text{ MeV})$

Fission barrier

Fusion properties

Transmission probability for a one-dimensional potential barrier

Classical  Quantum-mechanical  ?

$h\_omega$  - Curvature parameter of the parabolic potential describing the barrier (default value 3 MeV)  MeV

Probability for compound nucleus formation  $P_{\text{CN}}$

Take into account the Probability for compound nucleus formation  $P_{\text{CN}}$  according to V.Zagrebaev & W.Greiner, PRC78, 034610 (2008)

Fission barrier vanishing

Take into account the Fission barrier vanishing with

0 - "Barfit" - A.J.Sierk, PRC33(1986)2039

1 - "FisRot" - S.Cohen et al., An.P 82(1974)

Nuclear potential

Bass formalism

Wood-Saxon

$V_0 = 105$  MeV  
 $R_0 = 1.12$  fm  
 $a = 0.75$  fm

Fusion L-diffuseness  MeV

Calculation

L (Bfis=0) = 63  
 L critical = 87

L direct (@ Rint) = 1

L max (grazing) = 0  
 L max (LISE) = 0.0

Show Details & CS ?

Partial Cross Sections  
 Barrier properties as f(L)  
 Potentials  $V_i = f(R)$   
 T, PCN, dEx-chan as f(L)  
 Bass Fusion CS & Barrier  
 2D: Barrier  $V=f(R, L)$  & dVdR

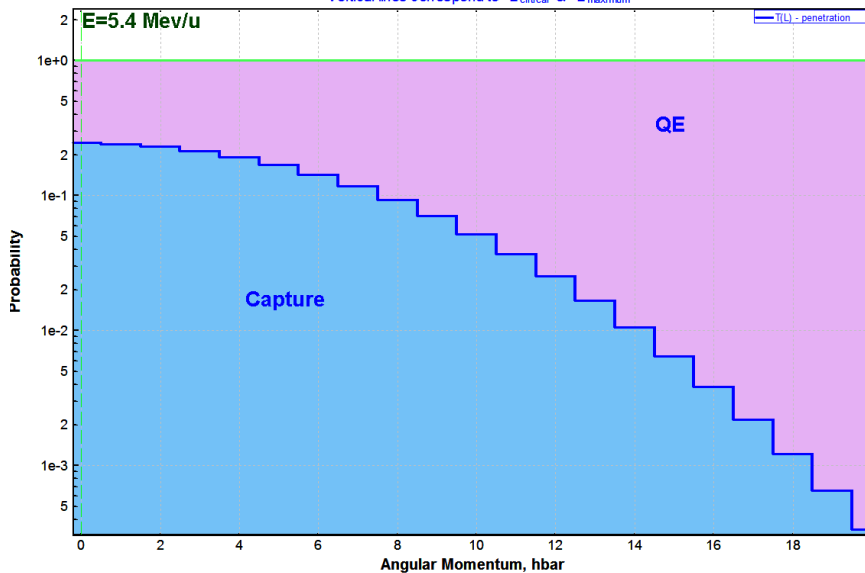
$T_l(E)$  denotes the transmission coefficient of the  $l$ -th partial wave through the barrier in the total potential

Hill-Wheeler expression

$$T_l(E) = (1 + \exp[2\pi(V(l, R_l) - E)/\hbar\omega])^{-1}$$

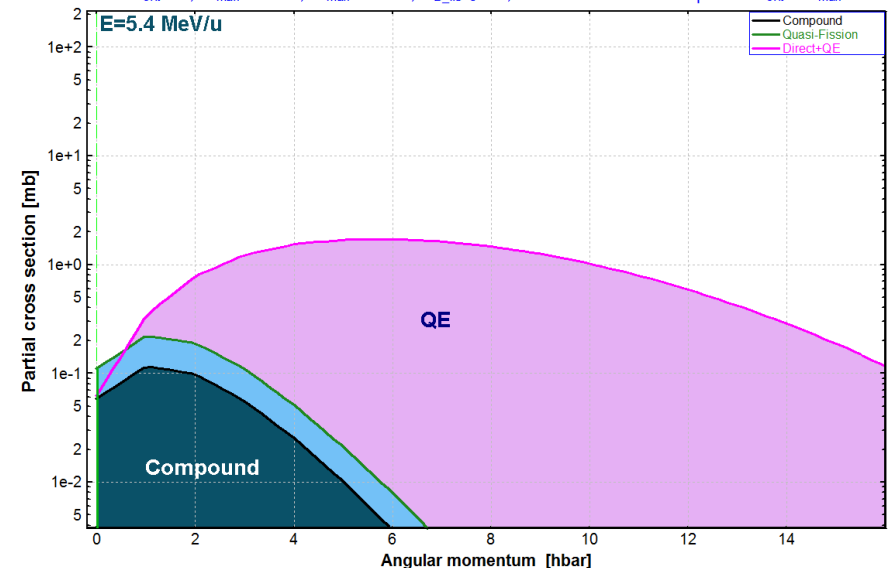
### Probabilities as f(L): $P_{\text{CN}}$ , $T(L)$

$^{238}\text{U}(5.4 \text{ MeV/u}) + ^{12}\text{C} \rightarrow ^{250}\text{Cf}^* (E_{\text{CM}}=61.7 \text{ MeV})$ ;  $h\_omega=5.0$   
 $L_{\text{crit}}=87$ ;  $L_{\text{max}}^{\text{Graz}}=0.0$ ;  $L_{\text{max}}^{\text{LISE}}=0.0$ ; Nuclear potential: WoodSaxon  
 Vertical lines correspond to  $L_{\text{critical}}$  &  $L_{\text{maximum}}$



### Partial cross sections

$^{238}\text{U}(5.4 \text{ MeV/u}) + ^{12}\text{C} \rightarrow ^{250}\text{Cf}^* (E_{\text{CM}}=61.7 \text{ MeV})$ ; [with  $P_{\text{CN}}$ , Penetration $^{QM}$ ]  
 Cross Sections[mb]: Intr=1.62e+01; Comp=3.70e-01; QF=7.16e-01; QE=1.51e+01;  
 $L_{\text{crit}}=87$ ;  $L_{\text{max}}^{\text{Graz}}=0.0$ ;  $L_{\text{max}}^{\text{LISE}}=0.0$ ;  $L_{\text{B\_fis}}=63$ ; Verticalical lines correspond to  $L_{\text{crit}}$  &  $L_{\text{max}}$



Fusion -> Residues

Evaporation settings:  $^{238}\text{U}(20.0 \text{ MeV/u}) + ^{12}\text{C} \rightarrow ^{250}\text{Cf}^* [E_x=204.5 \text{ MeV}]$

Fission barrier: [icon]

Fusion properties:

Transmission probability for a one-dimensional potential barrier:

Classical  Quantum-mechanical  ?

$\hbar\omega$  - Curvature parameter of the parabolic potential describing the barrier (default value 3 MeV)  MeV

Probability for compound nucleus formation  $P_{\{CN\}}$

Take into account the Probability for compound nucleus formation  $P_{\{CN\}}$  according to V.Zagrebaev & W.Greiner, PRC78, 034610 (2008)

Fission barrier vanishing

Take into account the Fission barrier vanishing with

0 - "Barfit" - A.J.Sierk, PRC33(1986)2039

1 - "FisRot" - S.Cohen et al. An.P 82(1974)

Nuclear potential:

Bass formalism

Wood-Saxon

$V_0 = 105 \text{ MeV}$   
 $R_0 = 1.12 \text{ fm}$   
 $a = 0.75 \text{ fm}$

Fusion L-diffuseness  MeV

Calculation:

L (Bfis=0) = 63  
 L critical = 87

L direct (@ Rint) = 99  
 L max (grazing) = 116.5  
 L max (LISE) = 117.1

Show Details & CS ?

Partial Cross Sections  
 Barrier properties as f(L)  
 Potentials  $V_i = f(R)$   
 T, PCN, dEx-chan as f(L)  
 Bass Fusion CS & Barrier  
 2D: Barrier  $V_i f(R, L)$  & dVdR

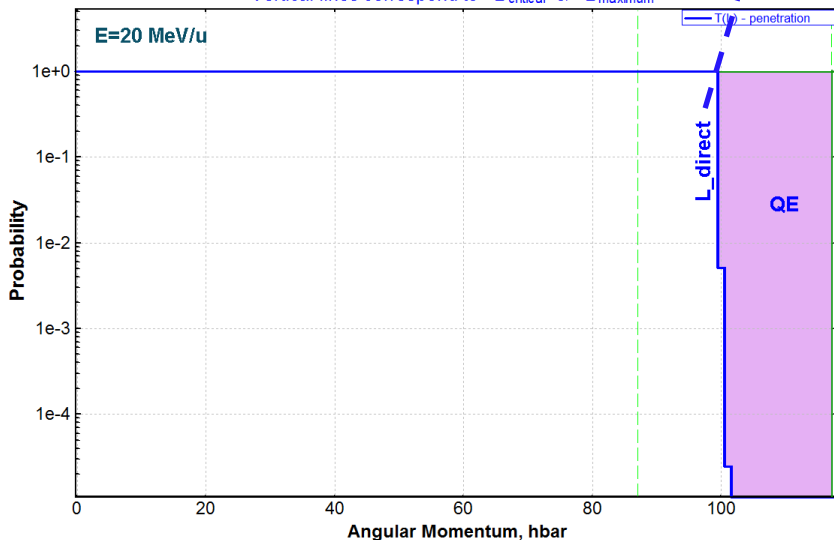
$T_l(E)$  denotes the transmission coefficient of the  $l$ -th partial wave through the barrier in the total potential

Hill-Wheeler expression

$$T_l(E) = (1 + \exp[2\pi(V(l, R_l) - E)/\hbar\omega])^{-1}$$

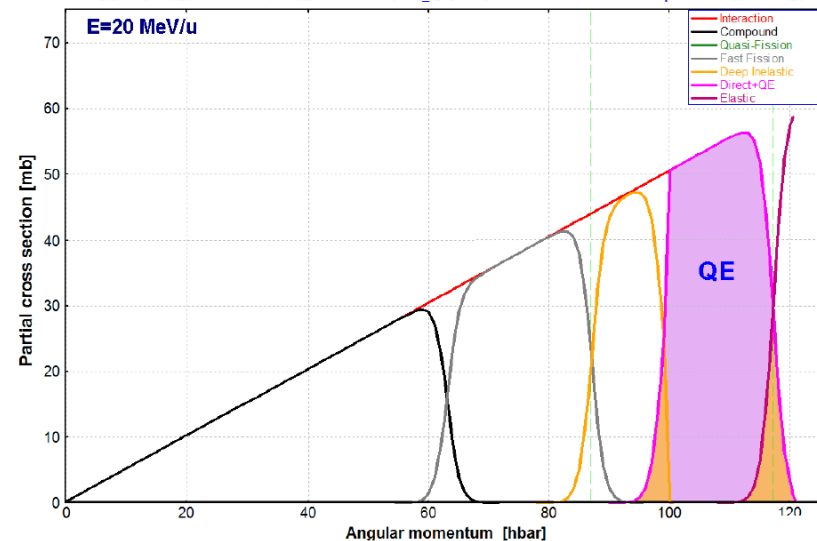
### Probabilities as f (L): $P_{CN}$ , $T(L)$

$^{238}\text{U}(20.0 \text{ MeV/u}) + ^{12}\text{C} \rightarrow ^{250}\text{Cf}^* (E_{CM}=228.4 \text{ MeV}); \hbar\omega=5.0$   
 $L_{crit}=87; L_{max}^{Graz}=116.5; L_{max}^{LISE}=117.1$ ; Nuclear potential: WoodSaxon  
 Vertical lines correspond to  $L_{critical}$  &  $L_{maximum}$



### Partial cross sections

$^{238}\text{U}(20.0 \text{ MeV/u}) + ^{12}\text{C} \rightarrow ^{250}\text{Cf}^* (E_{CM}=228.4 \text{ MeV}); [\text{with } P_{CN}, \text{Penetration}^{QM}]$   
 Cross Sections[mb]: Intr=3.48e+03; Comp=1.02e+03; QF=2.24e-09; FA=9.13e+02; DIC=5.42e+02; QE=1.01e  
 $L_{crit}=87; L_{max}^{Graz}=116.5; L_{max}^{LISE}=117.1; L_{B_{fis}=0}=63$ ; Verticalical lines correspond to  $L_{crit}$  &  $L_{max}$





## 1<sup>st</sup> step compound de-excitation plot

Fusion -> Residues

Evaporation settings: 238U(20.0 MeV/u) + 12C -> 250Cf\* (Ex=204.5MeV) Fission barrier

Fusion properties

Transmission probability for a one-dimensional potential barrier  
 Classical  Quantum-mechanical  ?  
 $h_{\omega}$  - Curvature parameter of the parabolic potential describing the barrier (default value 3 MeV)  MeV

Probability for compound nucleus formation P<sub>CN</sub>  
 Take into account the Probability for compound nucleus formation P<sub>CN</sub> according to V.Zagrebaev & W.Greiner, PRC78, 034610 (2008)

Fission barrier vanishing  
 Take into account the Fission barrier vanishing with  
 "Barfi" - A.J.Sierk, PRC33(1986)2039  
 "FisRot" - S.Cohen et al., An.P 82(1974);

Nuclear potential  
 Bass formalism  
 Wood-Saxon  
 V0 =  MeV  
 R0 =  fm  
 a =  fm

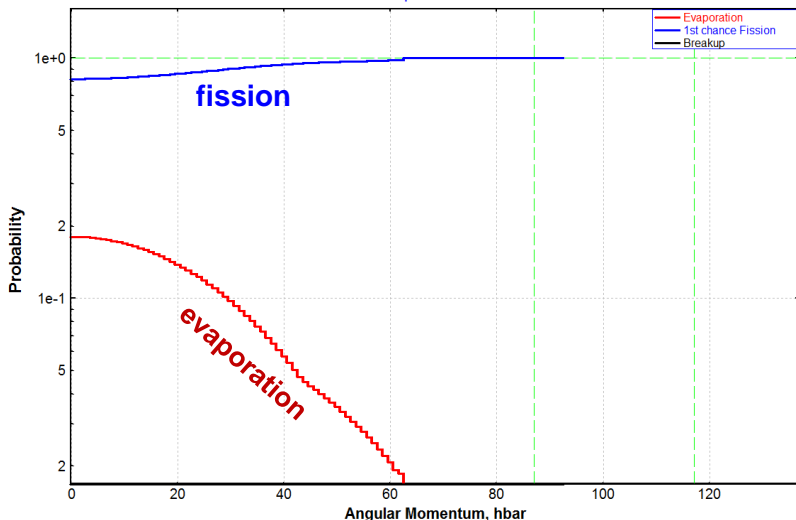
Calculation  
 L (Bfis=0) =   
 L critical =   
 L direct (@ Rint) =   
 L max (grazing) =   
 L max (LISE) =

Fusion L-diffuseness  MeV Show Details & CS ?

Partial Cross Sections  
 T.PCN de-exchan as f(L)  
 Barrier properties as f(L)  
 Potentials V = f(R)  
 Bass Fusion CS & Barrier  
 2D: Barrier V=f(R,L) & dVdR

### Probabilities as f(L): Compound 1st step de-excitation

$^{238}\text{U}(20.0 \text{ MeV/u}) + ^{12}\text{C} \rightarrow ^{250}\text{Cf}^* (E_{\text{CM}}=228.4 \text{ MeV}); h_{\omega}=5.0$   
 $L_{\text{crit}}=87; L_{\text{max}}^{\text{Graz}}=116.5; L_{\text{max}}^{\text{LISE}}=117.1; \text{Nuclear potential: WoodSaxon}$   
 Vertical lines correspond to  $L_{\text{critical}}$  &  $L_{\text{maximum}}$



238U(20.0 MeV/u) + 12C -> 250Cf\* (Ex=204.5MeV)

E<sub>LAB</sub>=4760.01 MeV, E<sub>CM</sub>=228.40 MeV

Fusion -> Residues

Settings

Nuclear Potential: Wood-Saxon  
 WS parameters: 105.0, 1.12, 0.75  
 P<sub>CN</sub> (probability of compound formation): Yes (take in: 1.00e+00  
 P<sub>CN</sub> at L=0: Yes (take in: 1.00e+00  
 Fission barrier vanishing: Yes (take in: 1.00e+00  
 Transmission probability for a 1-dimensional barrier: Quantum-Mechan: 1.00  
 Curvature parameter of the parabolic potential: 5.00  
 Fusion L-diffuseness: 1.00

Momentum (hbar)

L (Bfis=0)	63	
L critical	87	(E crit=176.9 MeV)
-----		
L direct (AA)	105.3	
L direct	99	used in calculations
-----		
L max (grazing)	116.5	
L max (LISE)	117.1	used in calculations

Cross sections (mb)

Partial (LISE++)

Interaction	3.483e+03
Compound	1.016e+03
Quasi-Fission	2.237e-09
Fast Fission	9.126e+02
Deep Inelastic	5.415e+02
Direct+QE	1.013e+03

Compound 1st step de-excitation channels (LISE++)

Fusion-Residue	6.436e+01
Fusion-Fission	9.516e+02
Fusion-Breakup	0.000e+00

Cross section used in calculations (beginning of target)

Complete Fusion: 2.101e+03  
 Use this factor for rates: 0.484

Bass cross section calculations

Fusion cross section	2.101e+03	mb
Fusion barrier	64.22	MeV
Fusion radius	9.10	fm
Barrier position	11.55	fm



Reaction Characteristics from Energy

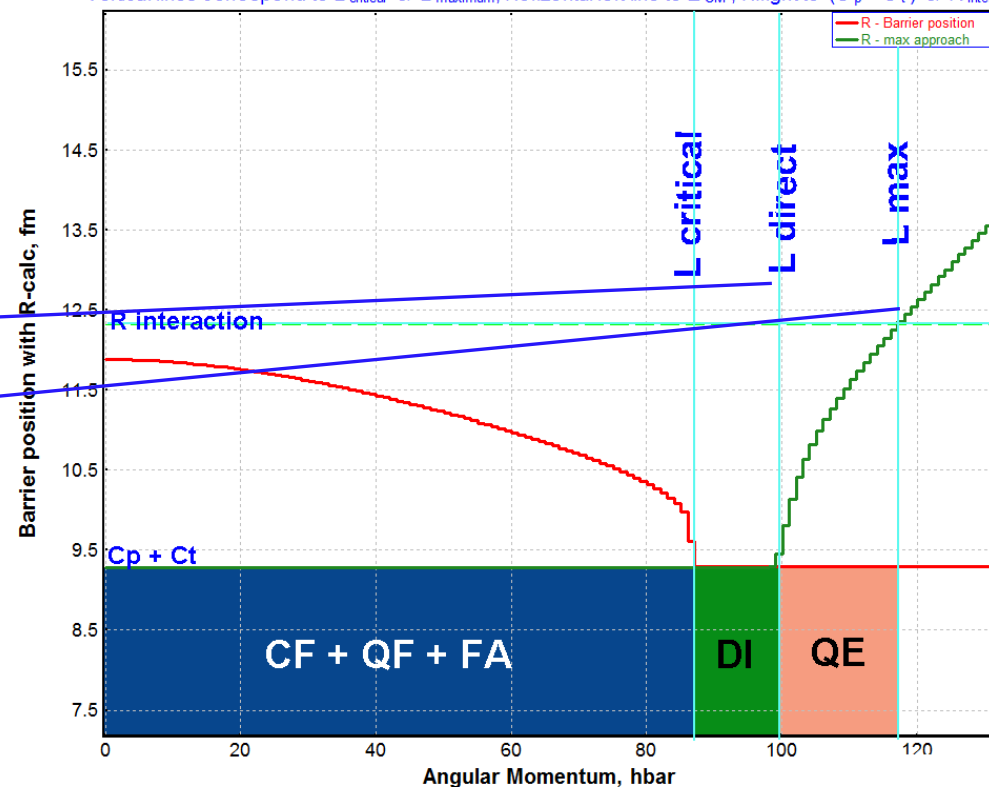
$^{238}\text{U} + ^{12}\text{C} \rightarrow ^{250}\text{Cf}^*$

parameter	value	dimension	definition	reference	formula
Elab	4760.0	MeV	Energy		
Elab/A	20.00	MeV / A	Energy per nucleon		Elab / Ap
Ecm	228.4	MeV	Energy in CMS		Elab * At / (At+Ap)
Ecm+Qgg	204.5	MeV	Excitation Energy		Ecm + Qgg
ETA	19.44		Coulomb parameter	Wilkie	$Z_p Z_t e^2 e / h v$
k	11.17	1/fm	asym. wave number	Wilcke	$\sqrt{2\mu a e m E_{cm} / h^2}$
a	1.74	fm	parameter	Hodgson	$Z_p Z_t e^2 e / 2 / E_{cm}$
QP_CM	18.94	deg	quarterpoint angle in CMS	Wilcke	$2 \arcsin(ETA / (k * R_{int}) - ETA)$
Theta_gr	18.94	deg	grazing angle in CMS	Wilcke	$2 \arctan(ETA / L_{max})$
LCg	67.0	h <sup>2</sup> /pi	crit. angle for collisions	Hodgson	$k^2 (h^2 / \pi^2) \sqrt{1 - 2a / (h^2 / \pi^2)}$
Lmax	116.5	h <sup>2</sup> /pi	graz. ang. mom. by QP_CM	Wilcke	$ETA * \cot(QP\_CM / 2)$
CSmax	517.1	mb	CS derived from Lmax	Wilcke	$\pi R_{max}^2 (L_{max} + CS)^2$
CS LCg	1956.6	mb	based on LCg	Hodgson	$\pi / k^2 * (LCg + 0.5)^2$
CStotal	3447.1	mb	total reaction CS	Kox	$\pi / 10^2 * 2^{(L_{max} + b^* \dots c + D)^2}$
Dgr	7.10	fm	dist. of appr. in graz. angle	Hodgson	$a^2 [1 + \text{cosec}(QP\_CM / 2)]$
AngleDir	6.40	deg	1st diffraction minimum	Valentin	$2 \arcsin(\pi \text{WaveLength} / 2 / R_t)$
FBarrier	64.22	MeV	fusion barrier height	Bass	
FRadius	9.10	fm	fusion radius	Bass	
FCS	2100.9	mb	fusion cross section	Bass	
CStotal	3339.5	mb	total reaction CS	Bass	

## Barrier amplitude and position as f(L): Barrier position

$^{238}\text{U}(20.0 \text{ MeV/u}) + ^{12}\text{C} \rightarrow ^{250}\text{Cf}^* (E_{cm}=228.4 \text{ MeV}); \quad h_{\omega}=5.0$

$L_{crit}=87; L_{max}^{Graz}=116.5; L_{max}^{USE}=117.1$ ; Nuclear potential: WoodSaxon; WS params: 105.0, 1.12, 0.  
Vertical lines correspond to  $L_{critical}$  &  $L_{maximum}$ , Horizontal left line to  $E_{CM}$ , H.right to  $(C_p + C_t)$  &  $R_{intera}$



Calculation

L (Bfis=0) = 40

L critical = 87

L direct (@ CpCt) = 99

L max (grazing) = 116.5

L max (@ Rint) = 117.1

Show Details & CS ?

**Barrier properties as f(L)**

Bass Fusion CS & Barrier

2D: Barrier V=f(R,L) & dVdR

**LISE++ still uses the Bass formalism to calculate fragment rates !!!!**

**238U(24.0 MeV/u) + 12C -> 250Cf\* (Ex=250.2MeV)**

E\_LAB=5712.01 MeV, E\_CM=274.08 MeV

**Fusion -> Residues**

**Settings**

Nuclear Potential: Wood-Saxon  
 WS parameters: 105.0, 1.12  
 P\_CN (probability of compound formation): No (No Q)  
 Fission barrier vanishing: Yes (take)  
 Transmission probability for a 1-dimensional barrier: Quantum-Me  
 Curvature parameter of the parabolic potential: 5.00  
 Fusion L-diffuseness: 1.00

**Momentum (hbar)**

L (Bfis=0)	63	
L critical	87	(E crit=176.9 MeV)
-----		
L direct (AA)	115.4	
L direct @ CpCt	110	used in calculations
-----		
L max (grazing)	131.7	
L max (LISE@Rint)	132.3	used in calculations

**Cross sections (mb)**

**Partial (LISE++)**

Interaction	3.700e+03	
Compound	8.469e+02	
Fast Fission	7.605e+02	
Deep Inelastic	9.112e+02	
Direct+QE	1.181e+03	

**Compound 1st step de-excitation channels (LISE++)**

Fusion-Residue	5.333e+01	
Fusion-Fission	7.935e+02	
Fusion-Breakup	0.000e+00	

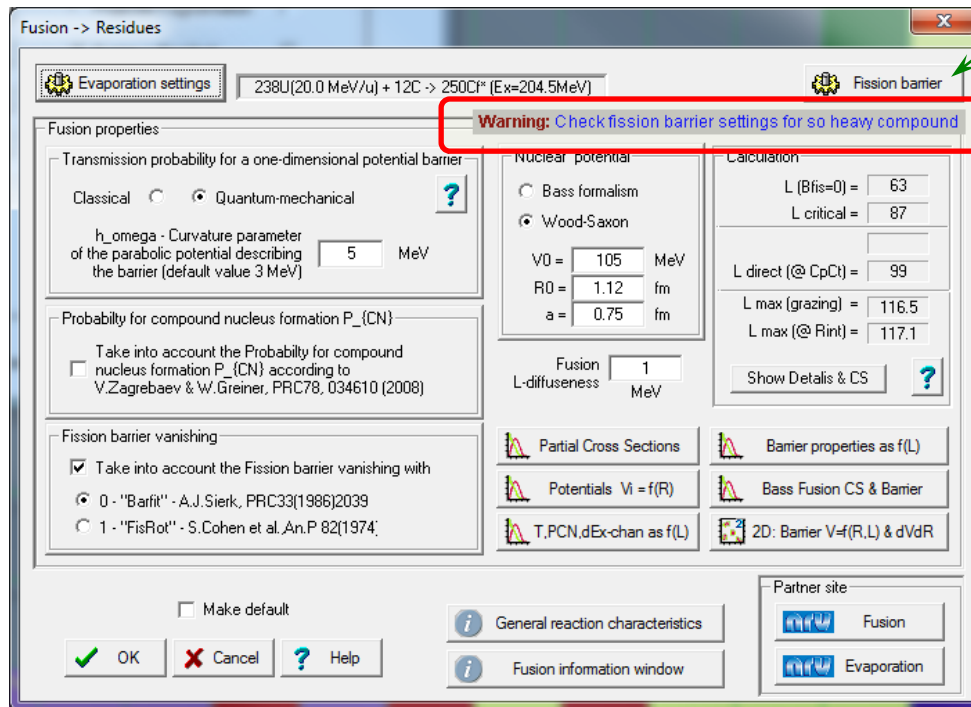
**Cross section used in calculations (beginning of LISE++)**

Complete Fusion	2.184e+03	
Use this factor for rates	0.388	

**Bass cross section calculations**

Fusion cross section	2.184e+03	mb
Fusion barrier	64.22	MeV
Fusion radius	9.10	fm
Barrier position	11.55	fm

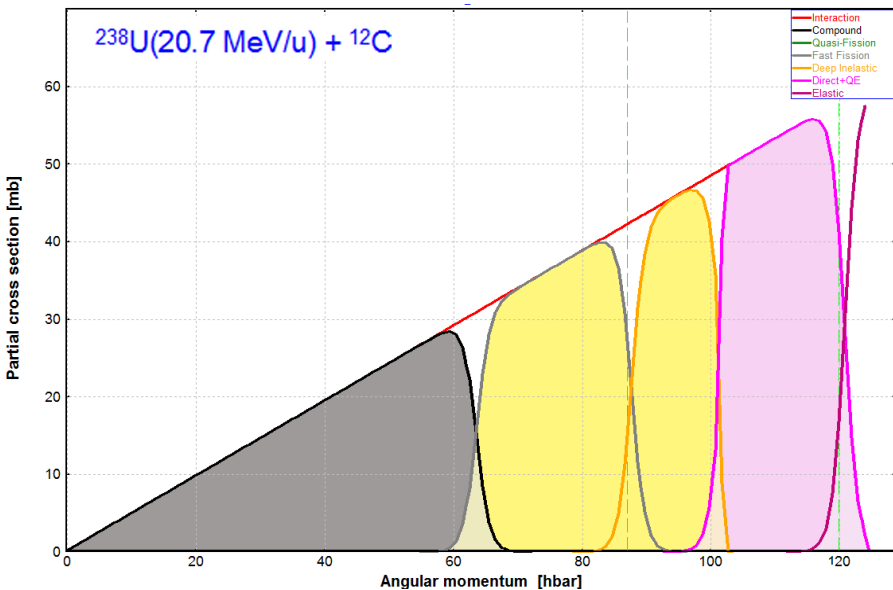
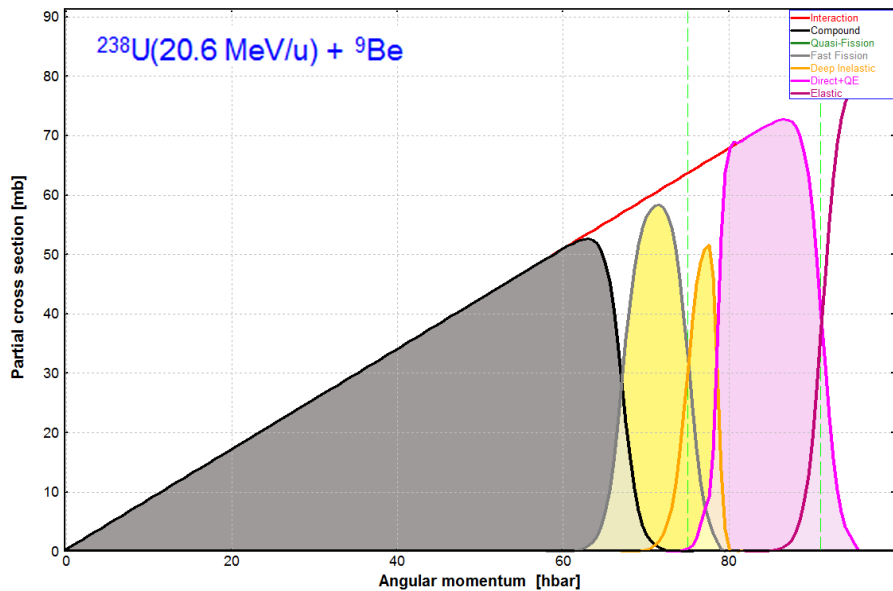
**You have to use this calculated factor later to take into account the analysis of partial cross sections**



Go to the Fission barrier dialog to modify settings for this SHN region

You will get this message if

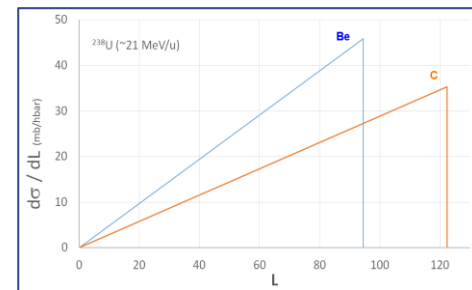
- The compound  $Z > 95$
- In-built fission model (Barfit, FisRot, or LDM) was selected
- "BarFac" parameter  $< 1.2$



average for 17-24 MeV/u range

		Targets	
Fission Barrier Vanishing	Reactions	Be	C
Sierk	DIC+FA	19%	42%
	Fusion-Fission	56%	29%
	QE	25%	29%
Cohen	DIC+FA	8%	29%
	Fusion-Fission	66%	41%
	QE	25%	29%

Momentum (hbar)	Be	C
L (Bfis=0)	67	63
L critical	75	87
L direct	79	101
L max (grazing)	90.5	118.9
L max (LISE)	91.0	119.5



**Carbon target.. 50% split... Why?**

This is due to difference of moments of inertia between C+U and Be+U just above where fission barrier go to zero

## Partial cross sections

$^{238}\text{U}(24.0 \text{ MeV/u}) + ^9\text{Be} \rightarrow ^{247}\text{Cm}^*$  ( $E_{\text{CM}}=208.3 \text{ MeV}$ ); [with  $P_{\text{CN}}$ , Penetration $^{\text{Q,M}}$ ]

Cross Sections[mb] : Intr=3.69e+03; Comp=1.66e+03; QF=1.54e-07; FA=4.16e+02; DIC=5.36e+02; QE=1.08e+03;

$L_{\text{crit}}=75$ ;  $L_{\text{max}}^{\text{Graz}}=99.9$ ;  $L_{\text{max}}^{\text{LISE}}=100.3$ ;  $L_{\text{B}_f=0}=67$ ; Vertical lines correspond to  $L_{\text{crit}}$  &  $L_{\text{max}}$



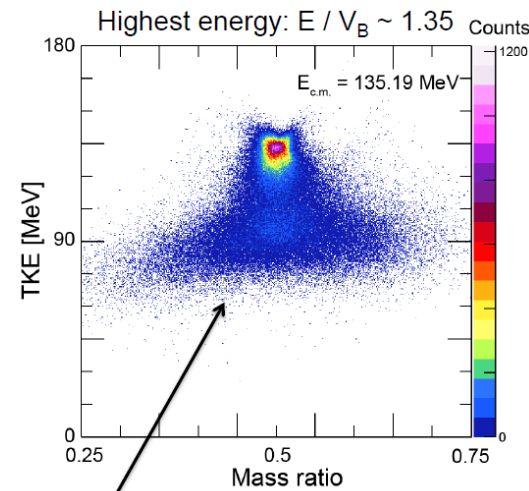
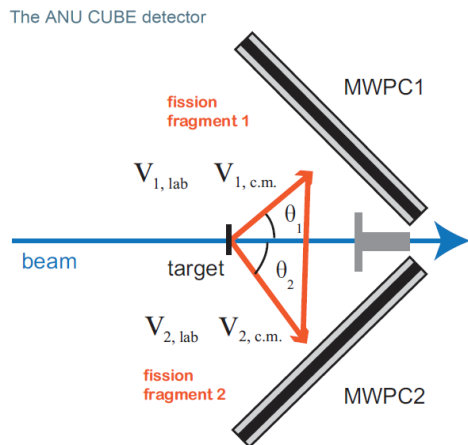
**Compound fission ~100%**  
**Fissile Z = 96**  
**High Excitation Energy**

**Sequential fission after DIC**  
**Fissile Z < 92**  
**High Excitation Energy**

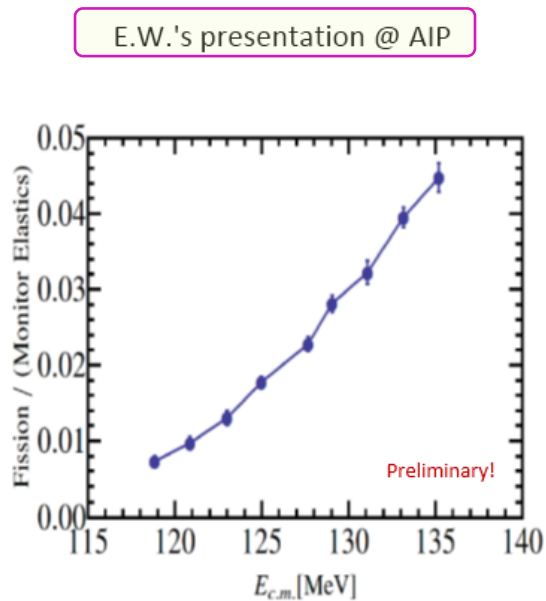
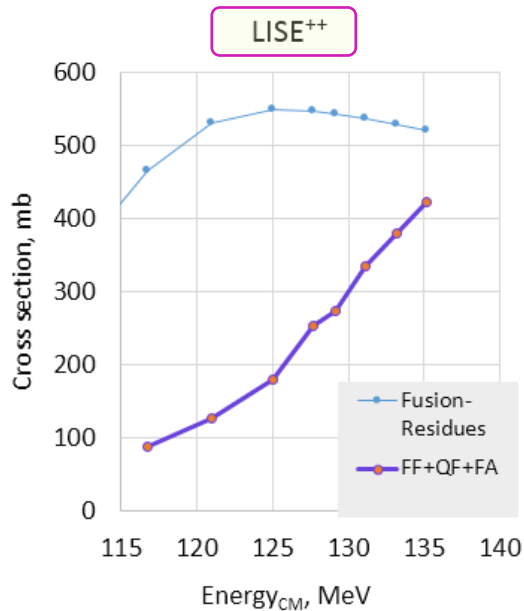
**Partially go to fission**  
**Fissile Z~92**  
**Low Excitation Energy**

[http://aip2014.org.au/cms/uploads/presentation/elizabeth\\_williams.pdf](http://aip2014.org.au/cms/uploads/presentation/elizabeth_williams.pdf)

Dr. Elizabeth Williams  
 Department of Nuclear Physics  
 The Australian National University, Canberra, ACT, Australia  
 AIP Congress, Canberra, ACT  
 9 December 2014



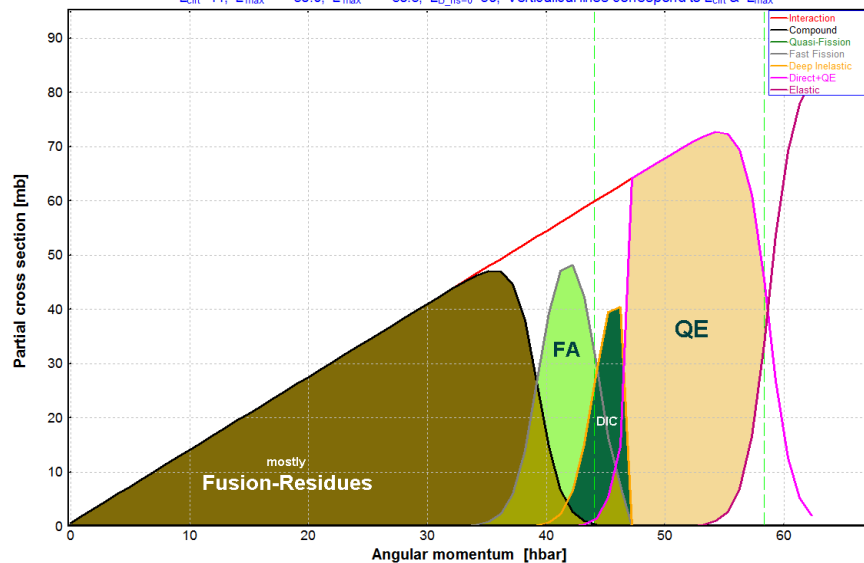
**Deep inelastic + Fusion-fission**  
 - Fusion-fission onset at  $E_{c.m.} \sim 125$  MeV



**12C**

### Partial cross sections

$^{36}\text{S}(12.0\text{ MeV/u}) + ^{12}\text{C} \rightarrow ^{48}\text{Ti}^* (E_{\text{CM}}=106.0\text{ MeV})$ ; [with  $P_{\text{CN}}$ , Penetration $^{\text{Q.M}}$ ]  
 Cross Sections[mb]: Intr=2.34e+03; Comp=1.06e+03; QF=1.49e-03; FA=2.81e+02; DIC=1.33e+02; QE=8.67e+02;  
 $L_{\text{crit}}=44$ ;  $L_{\text{max}}^{\text{Graz}}=58.0$ ;  $L_{\text{max}}^{\text{LISE}}=58.3$ ;  $L_{\text{B\_fis}}=39$ ; Vertical lines correspond to  $L_{\text{crit}}$  &  $L_{\text{max}}$



### Cross sections (mb)

Partial (LISE++)	
Interaction	2.338e+03
Compound	1.057e+03
Quasi-Fission	1.494e-03
Fast Fission	2.809e+02
Deep Inelastic	1.334e+02
Direct+QE	8.671e+02

### Compound 1st step de-excitation channels (LISE++)

Fusion-Residue	8.678e+02
Fusion-Fission	1.890e+02
Fusion-Breakup	0.000e+00

### Basic cross section calculations

Fusion cross section	1.044e+03	mb
Fusion barrier	14.49	MeV
Fusion radius	5.50	fm
Barrier position	8.80	fm

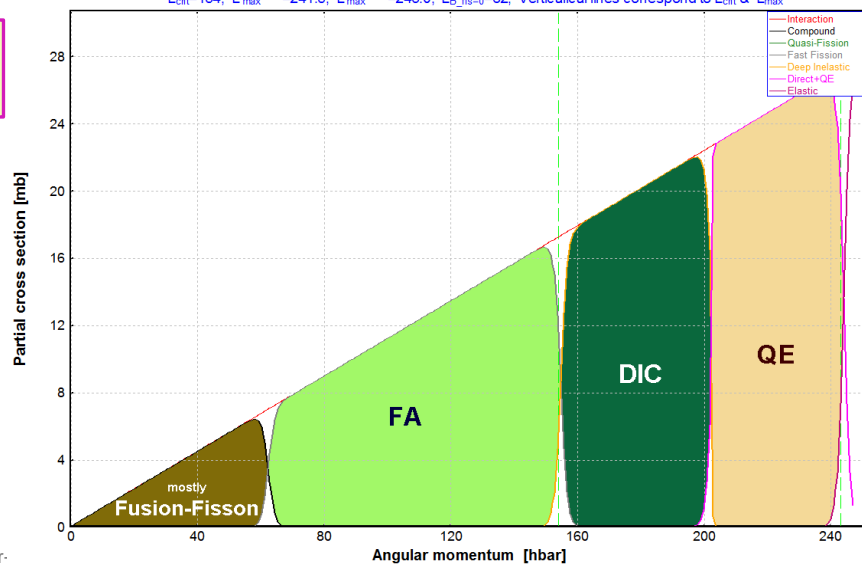
### Grazing Angle (deg)

Center-of-mass system	8.60
Laboratory system	2.14

**238U**

### Partial cross sections

$^{36}\text{S}(12.0\text{ MeV/u}) + ^{238}\text{U} \rightarrow ^{274}\text{Hs}^* (E_{\text{CM}}=374.7\text{ MeV})$ ; [with  $P_{\text{CN}}$ , Penetration $^{\text{Q.M}}$ ]  
 Cross Sections[mb]: Intr=3.33e+03; Comp=2.19e+02; QF=3.64e-01; FA=1.12e+03; DIC=9.41e+02; QE=1.05e+03;  
 $L_{\text{crit}}=154$ ;  $L_{\text{max}}^{\text{Graz}}=241.5$ ;  $L_{\text{max}}^{\text{LISE}}=243.0$ ;  $L_{\text{B\_fis}}=62$ ; Vertical lines correspond to  $L_{\text{crit}}$  &  $L_{\text{max}}$



### Cross sections (mb)

Partial (LISE++)	
Interaction	3.328e+03
Compound	2.191e+02
Quasi-Fission	3.641e-01
Fast Fission	1.121e+03
Deep Inelastic	9.407e+02
Direct+QE	1.047e+03

~2.04e3mb

### Compound 1st step de-excitation channels (LISE++)

Fusion-Residue	1.772e+01
Fusion-Fission	2.014e+02
Fusion-Breakup	0.000e+00

### Basic cross section calculations

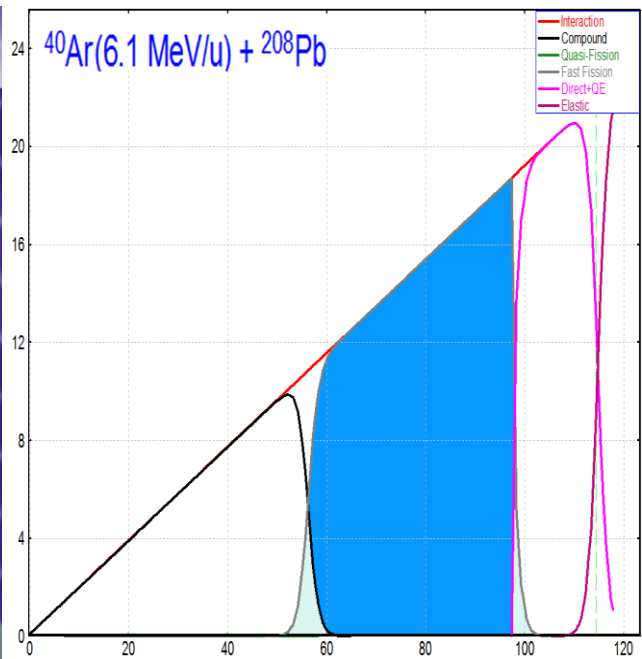
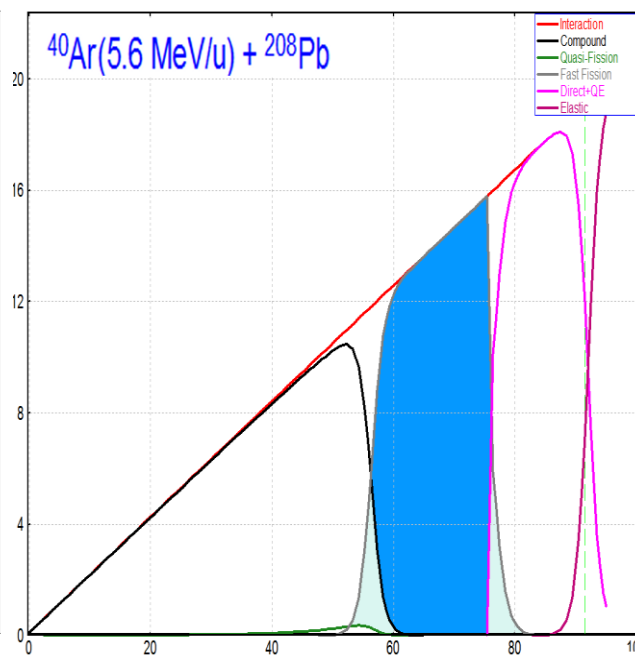
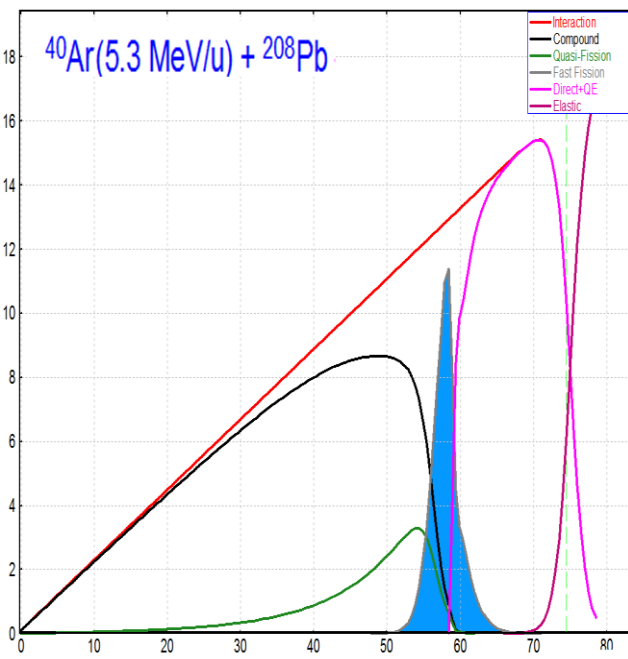
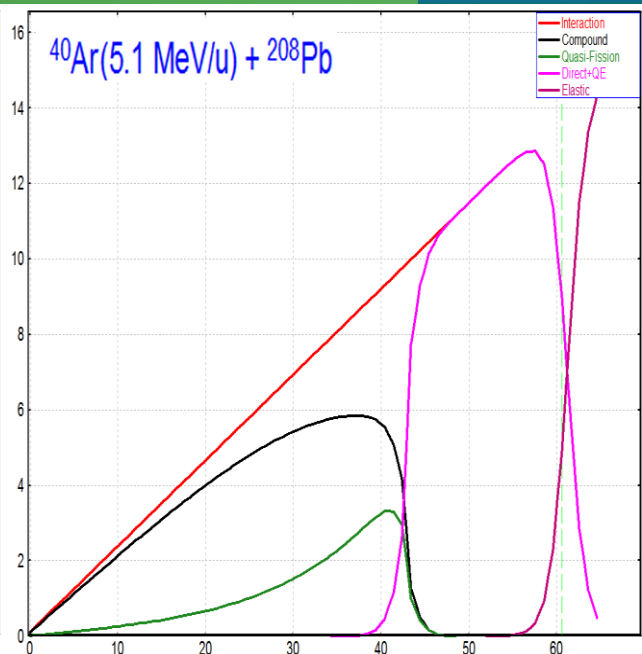
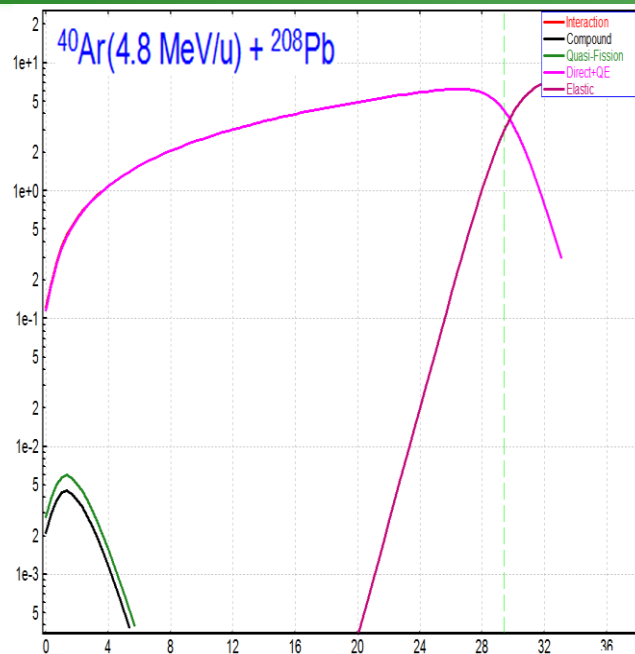
Fusion cross section	2.116e+03	mb
Fusion barrier	159.12	MeV
Fusion radius	10.40	fm
Barrier position	12.40	fm

### Grazing Angle (deg)

Center-of-mass system	30.97
Laboratory system	26.99



Energy, Lab MeV/u	Energy, CM MeV	Bass barrier MeV	ECM/B - 1 %	cross sections				
				Compound mb	QF mb	FA mb	DI mb	QE mb
4.8	160.8	161.9	-0.7%	1.5E-02	1.9E-02	0	0	1.1E+02
5.1	170.8	161.9	5.5%	1.6E+02	5.0E+01	0	0	2.2E+02
5.3	177.5	161.9	9.7%	3.1E+02	4.6E+01	4.4E+01	0	2.3E+02
5.6	187.6	161.9	15.9%	3.3E+02	5.0E+00	2.8E+02	0	2.7E+02
6.1	259.7	161.9	60.4%	3.1E+02	6.2E-01	6.2E+02	0	3.4E+02





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