1. Fission barrier dialog modification

2. Fusion dialogs
   - Potential energy
   - Potential pocket, $L_{\text{critical}}$, DIC
   - Fission barrier vanishing, $L_{B\text{fis}}=0$, Fast Fission (FA)
   - Compound Formation, Quasi-Fission
   - Barrier penetration, Quasi-Elastic (QE)
   - Compound de-excitation: Fusion – Fission or Residue?

3. LISE++ definitions and features of fusion mechanism

4. Examples:
   - $^{238}\text{U} (20\text{ MeV/u}) + \text{Be, C}$
   - $^{58}\text{Ni} + ^{60}\text{Ni}$
   - $^{36}\text{S} (12\text{ MeV/u}) + ^{12}\text{C}$, $^{238}\text{U}$
   - $^{40}\text{Ar} + ^{208}\text{Pb}$

Purpose:
implementation of angular momentum formalism into low-energy reactions

LISE++ 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 an 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

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

Barrier factor to describe experimental data or sophisticated calculations.
Fission barrier dialog modification

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

0. Sierk’s fission barrier is operating up to Z≤110 @ L=0 or Z ≤ 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,

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

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

O.Tarasov, 10-Apr-2015, East Lansing
Fusion-Residue and Fusion-Fission dialogs in LISE++

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

Do not hesitate to use Low-Energy reaction computing centers as NRV for more sophisticated solutions with Channel Coupling, Langevin equations and so on.
Coming back to the Eighties for definitions

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

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.
Potential Energy

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

\[ V_{\text{nucl}}(r) = -V_0 \left\{ 1 + \exp[(r - r_0(A_p^{1/3} + A_r^{1/3}))/a] \right\}^{-1} \]

Default NRV parameters

Potential energy plot

\(^{238}\text{U}(20.0 \text{ MeV}) + ^{9}\text{Be} \rightarrow ^{248}\text{Cm}\) (\(E_{\text{cm}}=173.6 \text{ MeV}\))

- \(L_{\text{CM}}=75\), \(L_{\text{max}} \text{Grass}=88.7\), \(L_{\text{max}} \text{LISE}=89.2\)
- Nuclear potential: WoodSaxon
- WS params: 105, 0, 12, 0.75

Vertical lines correspond to \((C_p + C_r)\) and \(L_{\text{reaction}}\). Right horizontal line to \(E_{\text{cm}}\)
Critical momentum: L-value corresponds to potential energy when the pocket is washed out. No fusion.

Deep Inelastic Collision region

\[ L_{\text{critical}} \leq L < L_{\text{direct}} \]

The potential pocket does not exist, and the EnergyCM is above the barrier.

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

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

\( L_{\text{cav}}=75; \ L_{\text{max}}^{\text{Gneq}}=88.7; \ L_{\text{max}}^{\text{LISE}}=89.2; \) Nuclear potential: Wood-Saxon; WS params: 105,0,1.12,0.75

Vertical lines correspond to \((C_p + C_i)\) and \(R_{\text{inter}}\); 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 EnergyCM is above the barrier.
Fission Barrier Vanishing as $f(L) \rightarrow$ Fast Fission (FA)

The potential pocket still exists, but no compound formation

Fast Fission region
$L_{B_{\text{fis}}=0} \leq L < L_{\text{critical}}$

Partial cross sections

O. Tarasov, 10-Apr-2015, East Lansing
Compound formation, Quasi-Fission: $^{48}\text{Ca} + ^{208}\text{Pb}$

**Fusion -> Residues**

- Fusion formation settings: $^{48}\text{Ca}(5.0 \text{ MeV/amu} + ^{208}\text{Pb}) + ^{295}\text{No}(E_x=91.9 \text{ MeV})$

**Fusion properties**

- Transmission probability for a one-dimensional potential barrier
  - Classical $\to$ Quantum-mechanical
  - $h_\text{omega}$ - Curvature parameter of the parabolic potential encircling the barrier (default value 3 MeV)
  - $V_B = 105$ MeV
  - $R_0 = 1.12$ fm
  - $a = 0.75$ fm

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

- Take into account the probability for compound nucleus formation $P_{\text{CN}}$ according to O. Tarasov, J. Phys. G 30, S3410 (2003)

**Partial cross sections**

- $^{48}\text{Ca}(5.0 \text{ MeV/amu} + ^{208}\text{Pb}) + ^{295}\text{No}(E_x=91.9 \text{ MeV})$ [with $P_{\text{CN}}$, Penetration$^{[2]}$ $^{[16]}$]

**Cross Sections (mb)**

- $^{48}\text{Ca}(5.0 \text{ MeV/amu} + ^{208}\text{Pb}) + ^{295}\text{No}(E_x=91.9 \text{ MeV})$ [with $P_{\text{CN}}$, Penetration$^{[2]}$ $^{[16]}$]

**Probaibilities as f (L): $P_{\text{CN}}, T(L)$**

- $^{48}\text{Ca}(6.0 \text{ MeV/amu} + ^{208}\text{Pb}) + ^{295}\text{No}(E_x=223.8 \text{ MeV})$, $h_\text{omega}=5.0$

**Angular Momentum, hbar**

- $L_{\text{min}}=170$, $L_{\text{max}}^{[1]}=140.9$, $L_{\text{max}}^{[2]}=143.9$, $L_{\text{max}}^{[3]}=45.9$. Vertical lines correspond to $L_{\text{min}}$, $L_{\text{max}}$

**Graphs**

- Graph of partial cross sections
- Graph of angular momentum distribution

**References**

- Physical Review C 78, 034610 (2008)
- O. Tarasov, 10-Apr-2015, East Lansing
Compound formation, Quasi-Fission: $^{58}\text{Fe} + ^{208}\text{Pb}$
Barrier penetration, Quasi-Elastic (QE) : $^{238}\text{U}(5.4 \text{ MeV/u}) + C$

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

Hill–Wheeler expression

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

Partial cross sections

$^{238}\text{U}(5.4 \text{ MeV/u}) + ^{12}\text{C} \rightarrow ^{250}\text{Cf}$ (ECFP: 61.7 MeV); with PCN, Penetration

Cross Sections (mb)$: L_{0.0}=1.62e+01; \text{Comp}=3.70e-01; \text{QE}=7.18e-01; \text{QE}=1.51e+01; L_{0.0}=87; L_{\text{max}}=0.0; L_{\text{max}}=0.0; L_{0.0}=63; \text{Vertical lines correspond to } L_{0.0} \text{ & } L_{\text{max}}$
Barrier penetration, Quasi-Elastic (QE) : $^{238}\text{U}(20.0\text{ MeV/u}) + \text{C}$

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

Hill–Wheeler expression

$$T_l(E) = (1 + \exp\{2\pi(V(l, R_l) - E)/\hbar\omega\})^{-1}$$
Fusion – Fission or Residue?

1st step compound de-excitation plot

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

Angular Momentum, hbar

Probability

evaporation

fission

238U(20.0 MeV/u) + 12C -> 250CF* (Eexc=204.5MeV)
E_LAB=4760.01 MeV, E_CN=228.40 MeV

Fusion = 4760.01 MeV, E_CN=228.40 MeV

Nuclear Potential
WS parameters
F_CN (probability of compound formation)
F_CN at L=0
Fission barrier vanishing
Transmission probability for a 1-dimensional barrier
Curvature parameter of the parabolic potential
Fusion L-diffuseness

Momentum (hbar)
L (Bf=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 2.103e+03
Use this factor for rates 0.464

Bass cross section calculations
Fusion cross section 2.103e+03 mb
Fusion barrier 64.22 MeV
Fusion radius 9.10 fm
Barrier position 11.55 fm

O.Tarasov, 10-Apr-2015, East Lansing
LISE++ reaction interpretation from R & L

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

$^{238}\text{U}(20.0\text{ MeV/amu}) + ^{12}\text{C} \rightarrow ^{250}\text{Cf}^*(E_{\text{CM}}=228.4\text{ MeV})$; $\hbar \omega_{\text{sym}}=5.0$

$L_{\text{crit}}=87$; $L_{\text{max,grazing}}=116.5$; $L_{\text{max,ISN}}=117.1$; Nuclear potential: WoodSaxon; WS params: 105.0, 12.0°

Vertical lines correspond to $L_{\text{crit}}$ & $L_{\text{max,ISN}}$. Horizontal left line to $E_{\text{CM}}$, right to $(C_p + C_t)$ & $R_{\text{vitera}}$

O.Tarasov, 10-Apr-2015, East Lansing
What cross sections will be used in LISE++ to get rates?

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

You have to use this calculated factor later to take into account the analysis of partial cross sections.
Fusion dialog warning message for barrier settings

You will get this message if:

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

Go to the Fission barrier dialog to modify settings for this SHN region
$^{238}\text{U} (20.6 \text{ MeV/u})$ with Be vs. C targets

This is due to difference of moments of inertia between $^{238}\text{U} + \text{Be}$ and $^{238}\text{U} + \text{C}$ just above where fission barrier go to zero.

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

average for 17-24 MeV/u range

<table>
<thead>
<tr>
<th>Fission Barrier Vanishing</th>
<th>Reactions</th>
<th>Be</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sierk</td>
<td>DIC+FA</td>
<td>19%</td>
<td>42%</td>
</tr>
<tr>
<td></td>
<td>Fusion-Fission</td>
<td>56%</td>
<td>29%</td>
</tr>
<tr>
<td></td>
<td>QE</td>
<td>25%</td>
<td>29%</td>
</tr>
<tr>
<td>Cohen</td>
<td>DIC+FA</td>
<td>8%</td>
<td>29%</td>
</tr>
<tr>
<td></td>
<td>Fusion-Fission</td>
<td>66%</td>
<td>41%</td>
</tr>
<tr>
<td></td>
<td>QE</td>
<td>25%</td>
<td>29%</td>
</tr>
</tbody>
</table>

Momentum (ℏbar)

- $L \ (\text{Bfis}=0)$: Be 67, C 63
- $L \text{ critical}$: Be 75, C 87
- $L \text{ direct}$: Be 79, C 101
- $L \text{ max (grazing)}$: Be 90.5, C 118.9
- $L \text{ max (LISE)}$: Be 91.0, C 119.5

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

This is due to difference of moments of inertia between $^{238}\text{U} + \text{Be}$ and $^{238}\text{U} + \text{C}$ just above where fission barrier go to zero.
Fission channels for $^{238}\text{U}$ (20 MeV/u) + Be,C reactions

**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
Experimental study of barrier distributions for $^{58}\text{Ni}+^{60}\text{Ni}$

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


The ANU CUBE detector

The ANU CUBE detector

Highest energy: $E / V_B \sim 1.35$

$E_{c.m.} = 135.19 \text{ MeV}$

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

Cross section, mb

Energy, $E_{c.m.}$, MeV

Fission / (Monitor Elastics)

Preliminary!
\[ ^{36}\text{S} (12 \text{ MeV/u}) + ^{12}\text{C}, ^{238}\text{U} \]

**Cross sections (mb)**

- **Partial (LISE++)**
  - Interaction \(2.338\pm03\)
  - Compound \(1.056\pm03\)
  - Quasi-Fission \(1.956\pm03\)
  - Fast Fission \(2.890\pm02\)
  - Deep Inelastic \(1.339\pm02\)
  - Fusion-Fission \(5.579\pm02\)

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

- Fusion-Residue \(0.578\pm02\)
- Fusion-Fission \(1.390\pm02\)
- Fusion-Breakup \(0.000\pm00\)

**Base cross section calculations**

- Fusion cross section \(1.044\pm03\) mb
- Fusion barrier \(14.49\) MeV
- Fusion radius \(5.50\) fm
- Barrier position \(8.80\) fm

**Grazing Angle (deg)**

- Center-of-mass system \(8.80\)
- Laboratory system \(2.19\)

---

**Cross sections (mb)**

- **Partial (LISE++)**
  - Interaction \(3.328\pm03\)
  - Compound \(2.191\pm02\)
  - Quasi-Fission \(3.641\pm01\)
  - Fast Fission \(1.121\pm03\)
  - Deep Inelastic \(9.407\pm02\)
  - Fusion-Fission \(1.697\pm03\)

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

- Fusion-Residue \(1.772\pm01\)
- Fusion-Fission \(2.014\pm02\)
- Fusion-Breakup \(0.000\pm00\)

**Base cross section calculations**

- Fusion cross section \(2.116\pm03\) mb
- Fusion barrier \(159.12\) MeV
- Fusion radius \(10.45\) fm
- Barrier position \(12.49\) fm

**Grazing Angle (deg)**

- Center-of-mass system \(30.97\)
- Laboratory system \(26.99\)
I would like to acknowledge to
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