Double arm time-of-flight spectrometer CORSET

Basic Characteristic of the spectrometer CORSET for binary reaction fragments (double ToF):

- Time Resolution: 150ps
- Mass resolution: ~2 a.m.u.
- Solid angle of each arm: 150 mstr
- Range of the measured angles:
  - In the reaction plane: From 20° to 160° ± 30°
  - Out of plane: ± 10°

Neutron spectrometer
- 8-50 neutron detectors DEMON

γ-rays spectrometer
- 4- 20 NaI(Tl) or BaF2 detectors
Heavy ion-induced reactions: binary channel

$^{64}\text{Ni} + ^{186}\text{W} \rightarrow ^{250}\text{No}^* \quad E^* \approx 40 \text{ MeV}$

M.G. Itkis, “Perspectives in Nuclear fission” Tokai, Japan, 14-16 March 2012
Presence of Qf in the medium composite systems (A~190-230u)

$^{12}\text{C} + ^{204}\text{Pb} \rightarrow ^{216}\text{Ra}$
$E_{lab} = 73 \text{ MeV} \quad E^* = 40.5 \text{ MeV}$

$^{48}\text{Ca} + ^{168}\text{Er} \rightarrow ^{216}\text{Ra}$
$E_{lab} = 194 \text{ MeV} \quad E^* = 40.4 \text{ MeV}$

M.G. Itkis, “Perspectives in Nuclear fission” Tokai, Japan, 14-16 March 2012
Mass-energy distributions for the $^{48}\text{Ca}+^{144,154}\text{Sm}$ at energies near the Coulomb barrier

$^{48}\text{Ca}+^{154}\text{Sm}\rightarrow^{202}\text{Pb}^*$  $E_{\text{lab}}=182$ MeV

$^{48}\text{Ca}+^{144}\text{Sm}\rightarrow^{192}\text{Pb}^*$  $E_{\text{lab}}=190$ MeV

Counts

$<\text{TKE}>$, MeV

mass, amu
Competition between fusion and QF processes: Hs (Z=108) composite systems

\[ ^{22}\text{Ne} + ^{249}\text{Cf} \rightarrow ^{271}\text{Hs} \]
\[ ^{26}\text{Mg} + ^{248}\text{Cm} \rightarrow ^{274}\text{Hs} \]
\[ ^{36}\text{S} + ^{238}\text{U} \rightarrow ^{274}\text{Hs} \]
\[ ^{58}\text{Fe} + ^{208}\text{Pb} \rightarrow ^{266}\text{Hs} \]

\[ E_{CN}^{*} = 52 \text{ MeV} \]
\[ E_{CN}^{*} = 64 \text{ MeV} \]
\[ E_{CN}^{*} = 56 \text{ MeV} \]
\[ E_{CN}^{*} = 48 \text{ MeV} \]

\[ E_{CN}^{*} = 29 \text{ MeV} \]
\[ E_{CN}^{*} = 35 \text{ MeV} \]
\[ E_{CN}^{*} = 35 \text{ MeV} \]
\[ E_{CN}^{*} = 33 \text{ MeV} \]

\[ Z_1 Z_2 = 980 \]
\[ 1152 \]
\[ 1472 \]
\[ 2132 \]

TKE distributions of symmetric fragments

\[ {}^{36}\text{S} + {}^{238}\text{U} \]
\[ <\text{TKE}> = 218 \pm 1 \text{ MeV} \]
\[ \sigma_{\text{TKE}} = 20 \text{ MeV} \]

\[ {}^{58}\text{Fe} + {}^{208}\text{Pb} \]
\[ <\text{TKE}> = 211 \pm 1 \text{ MeV} \]
\[ \sigma_{\text{TKE}} = 20 \text{ MeV} \]

M.G. Itkis, “Perspectives in Nuclear fission”
Tokai, Japan, 14-16 March 2012
Fusion probability $P_{CN}$ for the reactions with $^{26}\text{Mg}$ and $^{36}\text{S}$ ions

The properties of entrance channels strongly affect the reaction dynamics.

At the excitation energy near the barrier the estimated values of $P_{CN}$ are $\sim 70\%$ in the case of the Mg-induced reaction and $\sim 25\%$ in the S-induced reaction.

M.G. Itkis, “Perspectives in Nuclear fission”
Tokai, Japan, 14-16 March 2012
M.G. Itkis, “Perspectives in Nuclear fission”  
Tokai, Japan, 14-16 March 2012
Superasymmetric fission of superheavy nuclei

**W. Greiner** (International Workshop on Fusion Dynamics at the Extremes, 25-27 May 2000)

Superasymmetric fission of nuclei with $A \sim 200$ u

M.G. Itkis, “Perspectives in Nuclear fission” Tokai, Japan, 14-16 March 2012
Proposed experiment:
Supeasymmetric fission of No-nucleus \((^{48}\text{Ca}/^{208}\text{Pb})\)

\[ ^{48}\text{Ca} + ^{208}\text{Pb} \rightarrow ^{256}\text{No} \]

The reaction

\[ ^{12}\text{C} + ^{248}\text{Cm} \rightarrow ^{260}\text{No} \rightarrow ^{48}\text{Ca} + ^{208}\text{Pb} + 4n \]

- Energy close to the Coulomb barrier — the excitation of the CN is about 35-40 MeV when the shell effects still exist;
- The contribution of QF process in this reaction is negligible due to the small value of \(Z_1Z_2=576\)

\[ \sigma_{\text{QF}}/\sigma_{\text{cap}} \approx 20\% \]

M.G. Itkis, “Perspectives in Nuclear fission”
Tokai, Japan, 14-16 March 2012
Reactions with 48Ca-ions

\[ ^{48}\text{Ca} + ^{238}\text{U} \rightarrow ^{286}\text{112} \quad (E_{CN}^* = 35\text{MeV}) \]

\[ E_{CN}^* = 18\text{ MeV} \]

\[ \text{Yield (relative units)} \]

\[ \text{TKE (MeV)} \]

\[ 50 \quad 100 \quad 150 \quad 200 \]

\[ 250 \quad 100 \quad 150 \quad 200 \]

\[ Z=50 \quad N=82 \]

\[ 56\text{ MeV} \]

\[ 180 \quad 210 \quad 240 \]

\[ 120 \quad 150 \quad 180 \]

M.G. Itkis, “Perspectives in Nuclear fission” Tokai, Japan, 14-16 March 2012
Asymmetric QF in the superheavy composite systems

\[ {}^{36}\text{S}+{}^{238}\text{U} \rightarrow {}^{274}\text{Hs}^* \]
\[ E^*=46 \text{ MeV} \]

\[ {}^{48}\text{Ca}+{}^{238}\text{U} \rightarrow {}^{286}\text{Cn}^* \]
\[ E^*=35 \text{ MeV} \]

\[ {}^{64}\text{Ni}+{}^{238}\text{U} \rightarrow {}^{302}120^* \]
\[ E^*=31 \text{ MeV} \]
The widths of Qfasym mass distributions

While the relative contribution of QF to the capture cross section mainly depends on the reaction entrance channel properties, the features of asymmetric QF are determined essentially by the driving potential of composite system.

M.G. Itkis, “Perspectives in Nuclear fission” Tokai, Japan, 14-16 March 2012
Asymmetric QF

Normal

Reverse

Driving potential is calculated near the scission point in nrv.jinr.ru (proximity model)

M.G. Itkis, “Perspectives in Nuclear fission” Tokai, Japan, 14-16 March 2012
Asymmetric QF
Reverse

nrv.jinr.ru
(proximity model)

M.G. Itkis, “Perspectives in Nuclear fission” Tokai, Japan, 14-16 March 2012
136Xe + 248Cm

potential energy (MeV)

mass asymmetry

elongation (fm)

Z = 114-116

nrv.jinr.ru
(proximity model)

M.G. Itkis, “Perspectives in Nuclear fission” Tokai, Japan, 14-16 March 2012
Transition from Ca to Ni:
Mass-energy distribution for $^{250}\text{No}$
Mass-angle distributions of the reaction fragments at $E^* \approx 40$ MeV


<table>
<thead>
<tr>
<th>Reaction</th>
<th>$&lt;A&gt;$ \text{amu}</th>
<th>$&lt;\text{TKE}&gt;$ \text{MeV}</th>
<th>$K_0$ \text{mb}</th>
<th>$\Delta \theta$ \text{deg.}</th>
<th>$\Delta \tau \times 10^{-21}$ \text{c}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{44}\text{Ca} + ^{206}\text{Pb}$</td>
<td>75</td>
<td>178</td>
<td>6,0</td>
<td>231</td>
<td>$\sim 4,0$</td>
</tr>
<tr>
<td></td>
<td>116</td>
<td>200</td>
<td>16,7</td>
<td>$\geq 270$</td>
<td>$\geq 32,4$</td>
</tr>
<tr>
<td>$^{64}\text{Ni} + ^{186}\text{W}$</td>
<td>80</td>
<td>187</td>
<td>7,0</td>
<td>226</td>
<td>$\sim 4,0$</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>200</td>
<td>16,7</td>
<td>$\geq 270$</td>
<td>$\geq 30,2$</td>
</tr>
</tbody>
</table>

![Graphs showing mass-angle distributions](image-url)
$E^*_{\text{CN}} \approx 45 \text{MeV}$

$Z_t Z_p$

1840

2444

2576

$^{48}\text{Ca}^{238}\text{U} \rightarrow ^{286}\text{Cn}$

$Y(A_{\text{CN}}/2 \pm 20) = 12\%$

34 u

$^{58}\text{Fe}^{244}\text{Pu} \rightarrow ^{302}\text{120}$

$Y(A_{\text{CN}}/2 \pm 20) = 8\%$

22 u

$^{64}\text{Ni}^{238}\text{U} \rightarrow ^{302}\text{120}$

$Y(A_{\text{CN}}/2 \pm 20) = 4\%$

11 u

Viola Systematics

70%

$\leq 2\%$

$\leq 0.2\%$

for $A_{\text{CN}}/2 \pm 20$
Cross section for the $^{64}\text{Ni}+^{238}\text{U}$ reaction

- The capture cross section is about a few hundred millibarns at energy above the Coulomb barrier (about 4-5 times less than for the reaction $^{48}\text{Ca}+^{238}\text{U}$).

- The formation cross section of fragments with masses $A_{\text{CN}}/2\pm 20$ u is one order of magnitude less compare with Ca-induced reactions.

- The estimated value of formation probability of compound nucleus formed in the reaction $^{64}\text{Ni}+^{238}\text{U}$ drops three orders of magnitude with respect to the $^{48}\text{Ca}+^{238}\text{U}$ reaction. This is unfortunately a limiting factor.

- Thus, we conclude that the reaction $^{64}\text{Ni}+^{238}\text{U}$ is not suitable for the synthesis of the synthesis of element Z=120.

PLB 686 (2010) 227

M.G. Itkis, “Perspectives in Nuclear fission”
Tokai, Japan, 14-16 March 2012
Conclusion

• While the relative contribution of QF to the capture cross section mainly depends on the reaction entrance channel properties, the features of asymmetric QF are determined essentially by the driving potential of a composite system.

• The fragment yield increases when the both formed fragments are close to nuclear shells as in the case of QF (asymmetric QF), as well as in the case of fusion-fission (bimodal fission, asymmetric fission, superasymmetric fission).

• At the transition from Ca to Ni projectiles the contribution of QF process rises sharply and Ni ions is not suitable for the synthesis of element Z=120 in the complete fusion reactions.

• An alternative way for further progress in SHE can be achieved using the deep-inelastic or QF reactions. To estimate the formation probabilities of SHE in these reactions the additional investigations are needed.
Collaboration

I.M. Itkis, M.G. Itkis, G.N.Knyazheva, E.M. Kozulin
Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia

F. Goennenwein
Physikalisches Institut, Universität Tübingen, 72076 Germany

E. Vardaci
INFN and Dipartamento di Scienze Fisiche dell’Università di Napoli, Napoli, Italy

F. Hanappe
Université Libre de Bruxelles, Bruxelles, Belgium

O. Dorvaux, L. Stuttge
Institut Pluridisciplinaire Hubert Curien, Strasbourg, France

W. Trzaska
Department of Physics, University of Jyväskylä, Finland

Thank you for your attention!
Reactions with $^{208}$Pb target

$^{48}$Ca + $^{208}$Pb → $^{256}$No ($E^* = 33$ MeV)

$^{50}$Ti + $^{208}$Pb → $^{258}$Rf ($E^* = 29$ MeV)

$^{58}$Fe + $^{208}$Pb → $^{266}$Hs ($E^* = 32.3$ MeV)

$^{86}$Kr + $^{208}$Pb → $^{294}$118 ($E^* = 26$ MeV)