VI[th] LATIN AMERICAN SYMPOSIUM ON NUCLEAR PHYSICS AND APPLICATIONS 2005

Fusion hindrance and quasi-fission in heavy-ion induced reactions: disentangling the effect of different parameters

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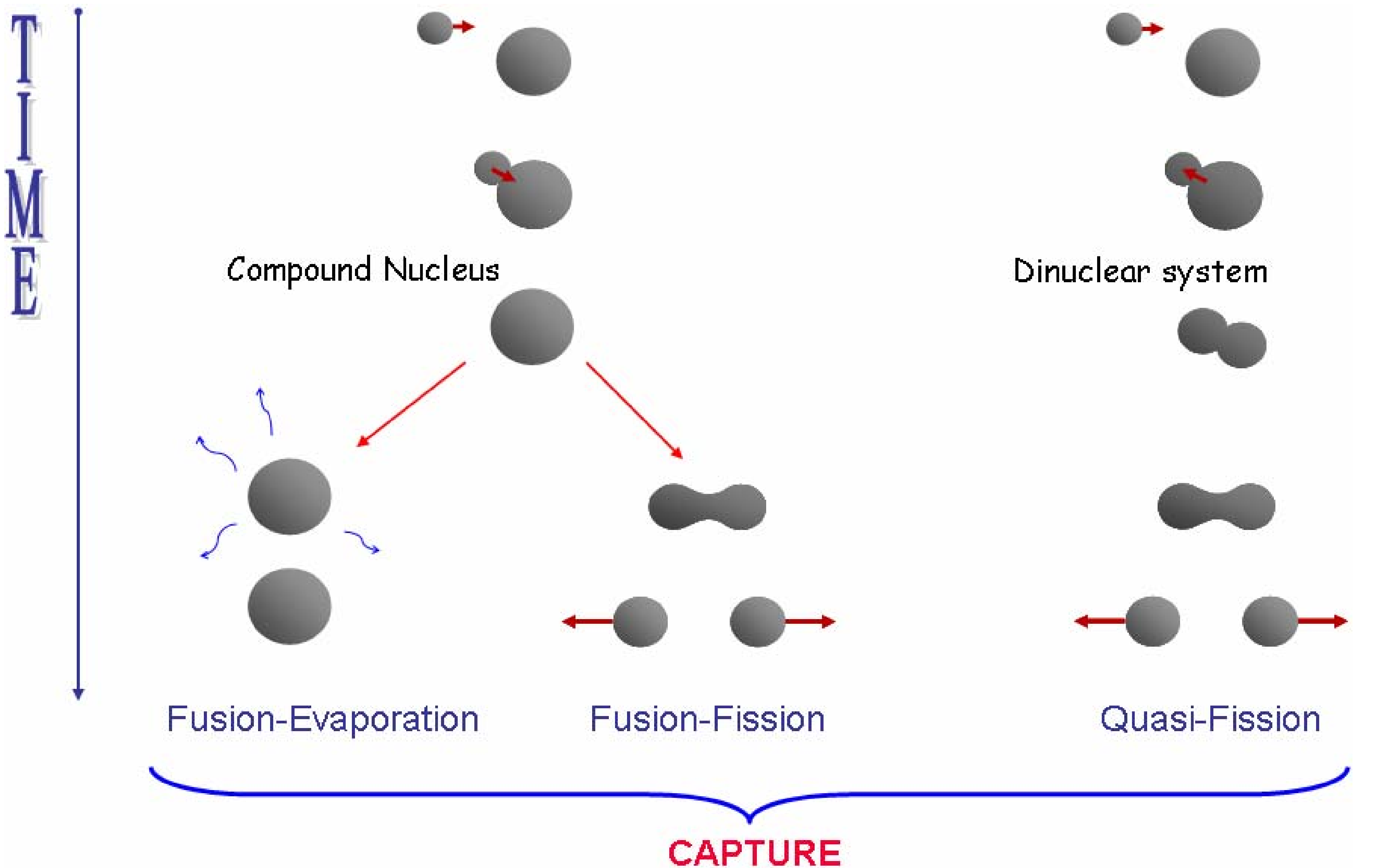
The capture process



The Quasi-Fission process

Factors affecting FF/QF competition

- Excitation energy
- Angular momentum
- Entrance channel mass asymmetry
- Shell effects
- Nucleus deformation and orientation

Experimental signatures for QF

- Broader FF Mass Distributions
- Larger anisotropies in FF angular distributions
- Lower ER yields
- Unexpected *n* and γ multiplicities

Three steps to SHE's

$$\sigma_{ER} = \sigma_{capt} \cdot P_{CN} \cdot P_{surv}$$

Capture of two nuclei in the attractive potential pocket.

Probability of forming a compact compound nucleus.

Survival probability against fission from the compact shape.

For optimization of ER formation the challenge is to understand which parameters influence σ_{capt} and P_{CN}

Our goal

- studying the mass asymmetry dependence of the fusion hindrance and the onset of the QF mechanism
- searching for shell effects on heavy-elements fusion-fission
- studying the influence of nuclear deformation/orientation on FF/QF competition

Our observables:

- ER cross sections
- FF Mass-Energy and angular distributions

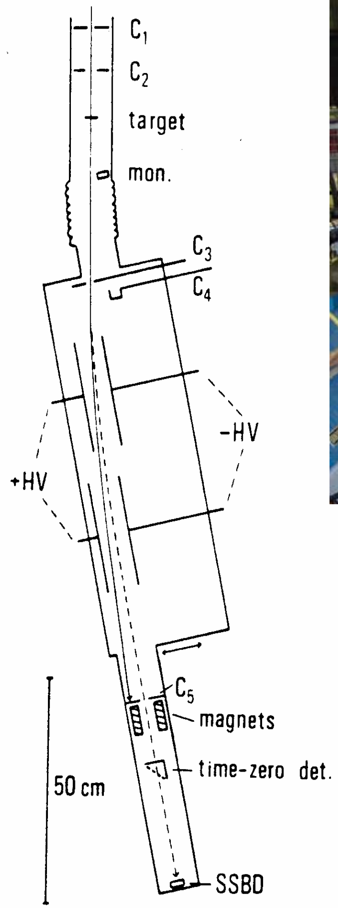
Desired:

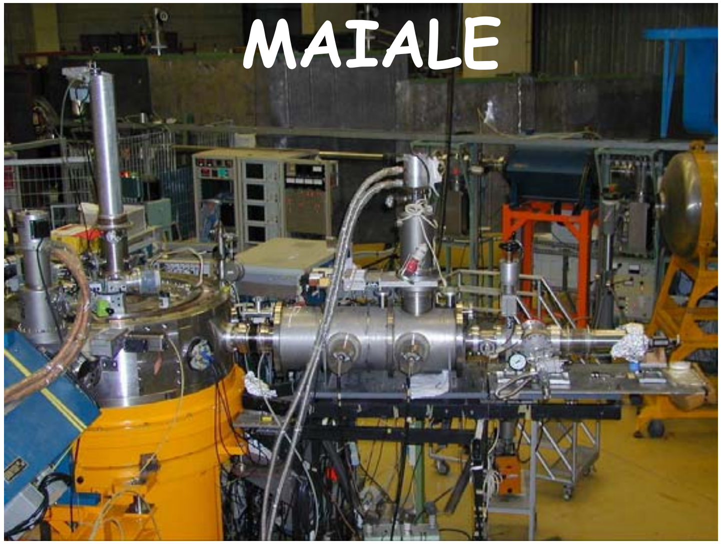
- *n* and γ multiplicities

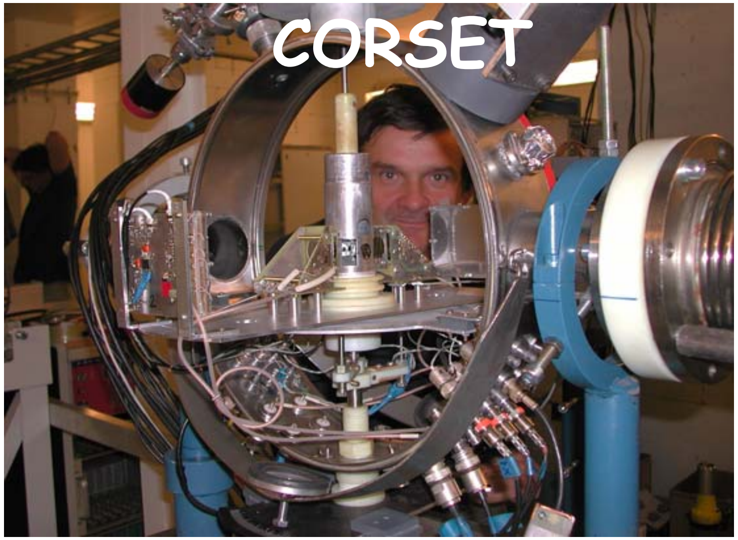
Reactions studied (2000-2005)

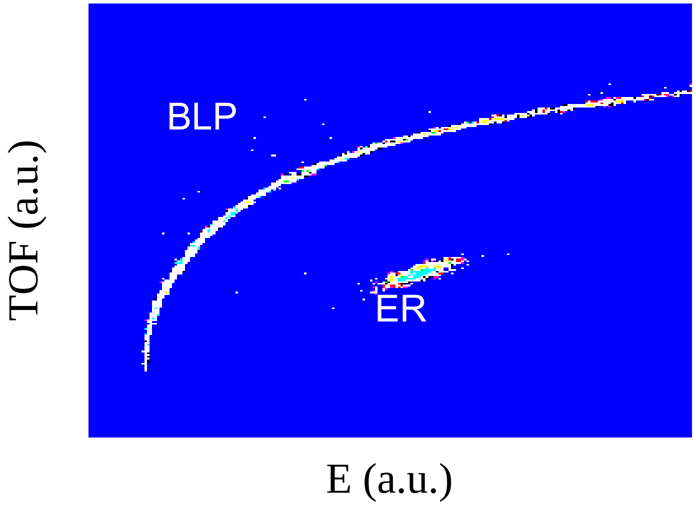
		E_{lab} MeV	E^* MeV
^{12}C	$+ ^{209}Bi \rightarrow ^{221}Ac$	62-73	23-45
	$+ ^{204}Pb \rightarrow ^{216}Ra$	56-90	23-55
	$+ ^{206}Pb \rightarrow ^{218}Ra$	56-85	21-48
	$+ ^{208}Pb \rightarrow ^{220}Ra$	56-90	20-51
^{48}Ca	$+ ^{168}Er \rightarrow ^{216}Ra$	182-208	29-51
	$+ ^{170}Er \rightarrow ^{218}Ra$	180-208	49-51
	$+ ^{144}Sm \rightarrow ^{192}Pb$	178-245	30-80
	$+ ^{154}Sm \rightarrow ^{202}Pb$	180-252	47-101
^{40}Ca	$+ ^{154}Sm \rightarrow ^{194}Pb$	165-200	48-76
^{16}O	$+ ^{186}W \rightarrow ^{202}Pb$	76-132	45-100
^{16}O	$+ ^{194}Pt \rightarrow ^{210}Rn$	72-130	36-90
^{34}S	$+ ^{176}Yb \rightarrow ^{210}Rn$	140-190	43-85

Experimental set-up @ LNL

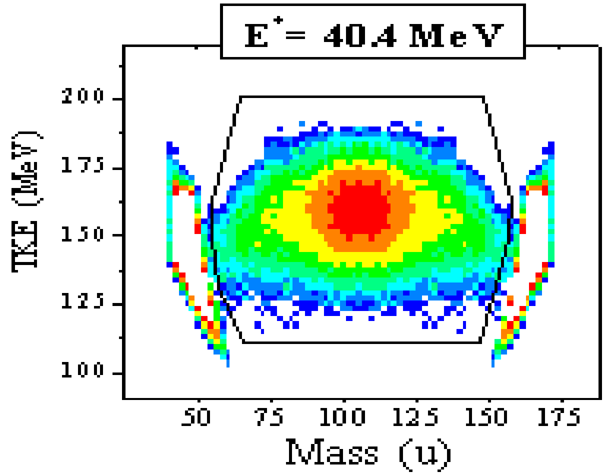




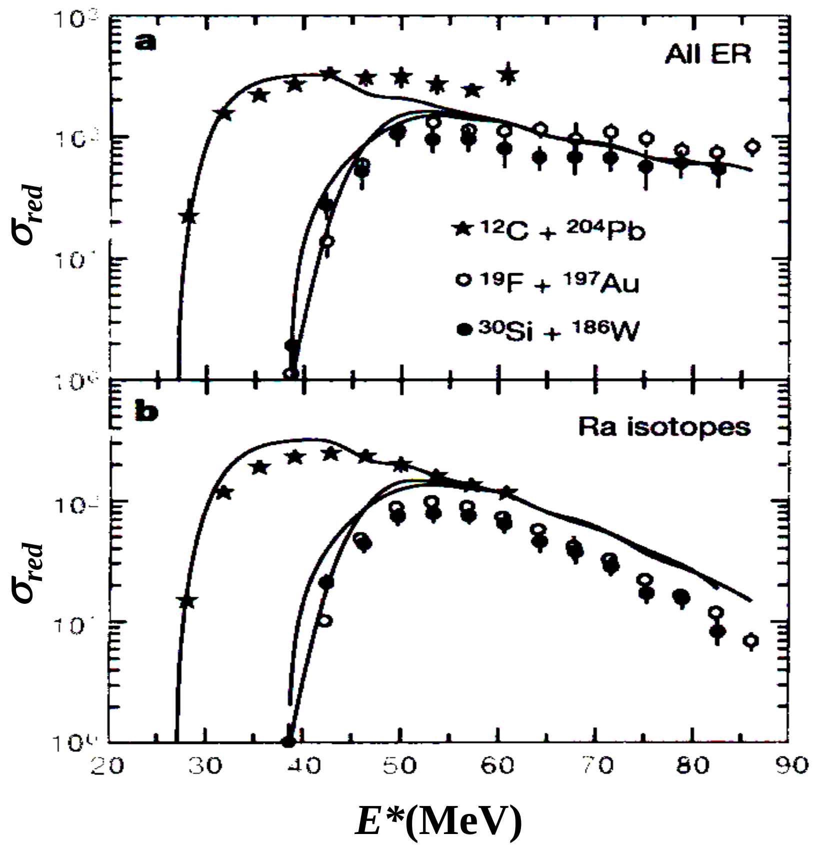




$$^{48}Ca + ^{168}Er \rightarrow ^{216}Ra$$



Fusion hindrance



$$\sigma_{ER} = \pi\lambda\!\!\!^{-2} \sum_{\ell=0}^{\infty} (2\ell+1) T_{\ell}(E)(1 - P_{fiss}(\ell, E^*))$$

Division by $\pi\lambda\!\!\!^{-2}$ gives the reduced cross section σ_{red}.

At beam energies sufficiently high above the Coulomb barrier $T_{\ell} \approx 1$ for all ℓ which lead to ERs

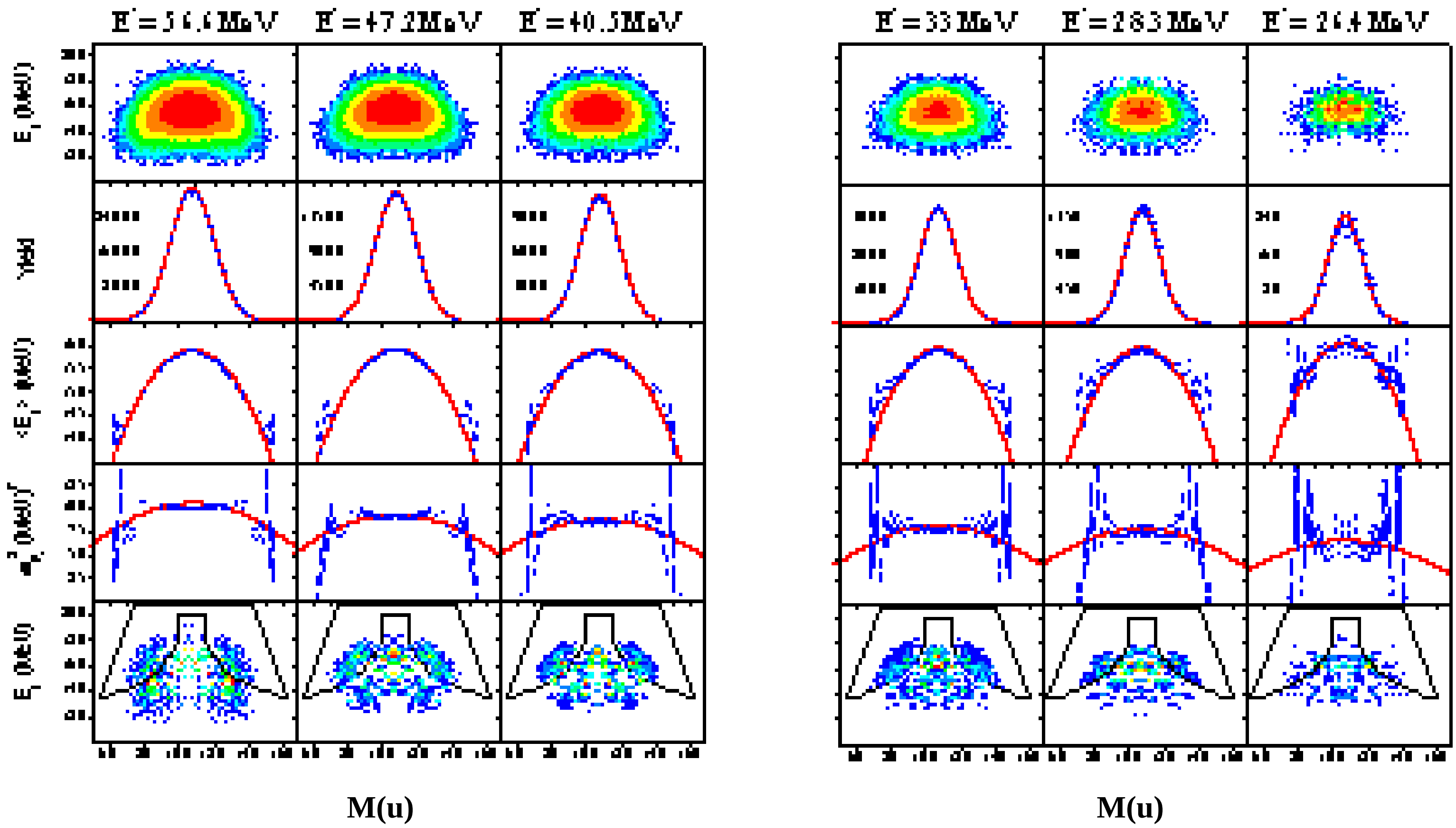
$$\sigma_{red} = \sum_{\ell=0}^{\infty} (2\ell+1)(1 - P_{fiss}(\ell, E_{exc}))$$

Thus at the same E* different reactions leading to the same CN should give the same σ_{red}, as long as no system-dependent fusion suppression exists.

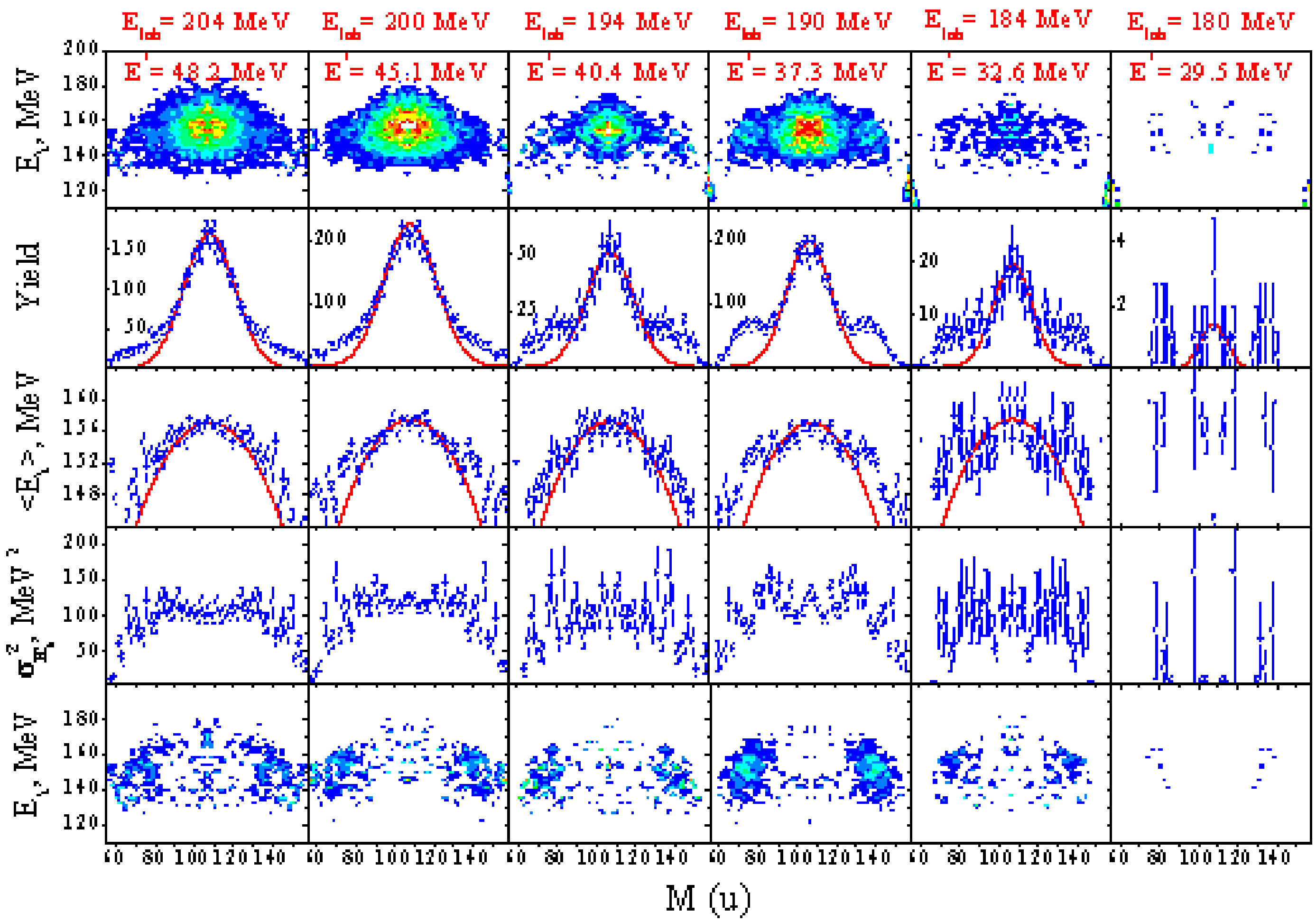
“Unexpected inhibition of fusion in nucleus-nucleus collisions”

A.C. Berriman et al., Nature 413 (2001) 144

FF Mass-Energy distributions: $^{12}C + ^{204}Pb \rightarrow ^{216}Ra^*$



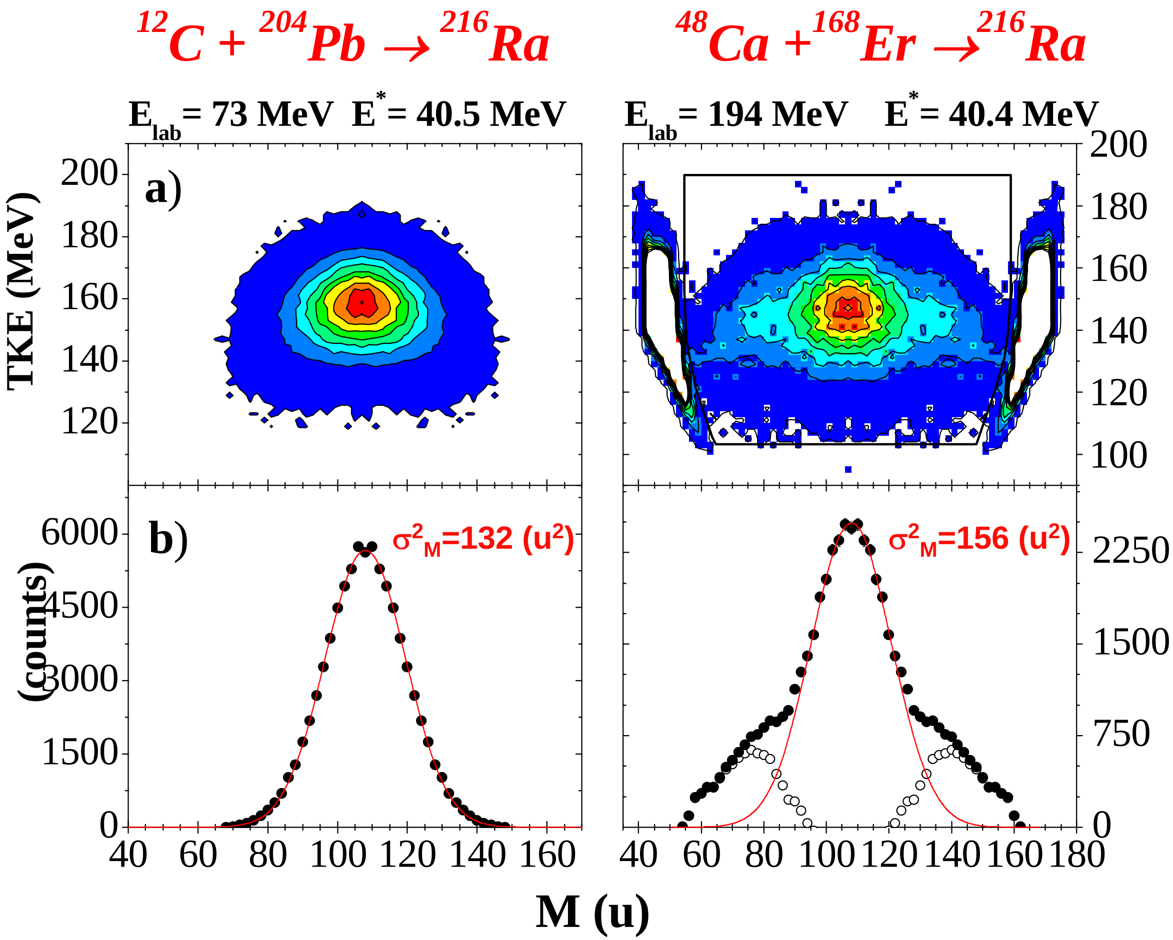
FF Mass-Energy distribution: $^{48}Ca+^{168}Er \rightarrow ^{216}Ra^*$



The relative yield of the asymmetric component increases with the decreasing E*

A. Yu. Chizhov et al., Phys. Rev. C 67 (2003) 011603

Entrance channel dependence of asymmetric fission



The contribution of asymmetric fission in ^{216}Ra* populated at the same E* in the two entrance channels is quite different.

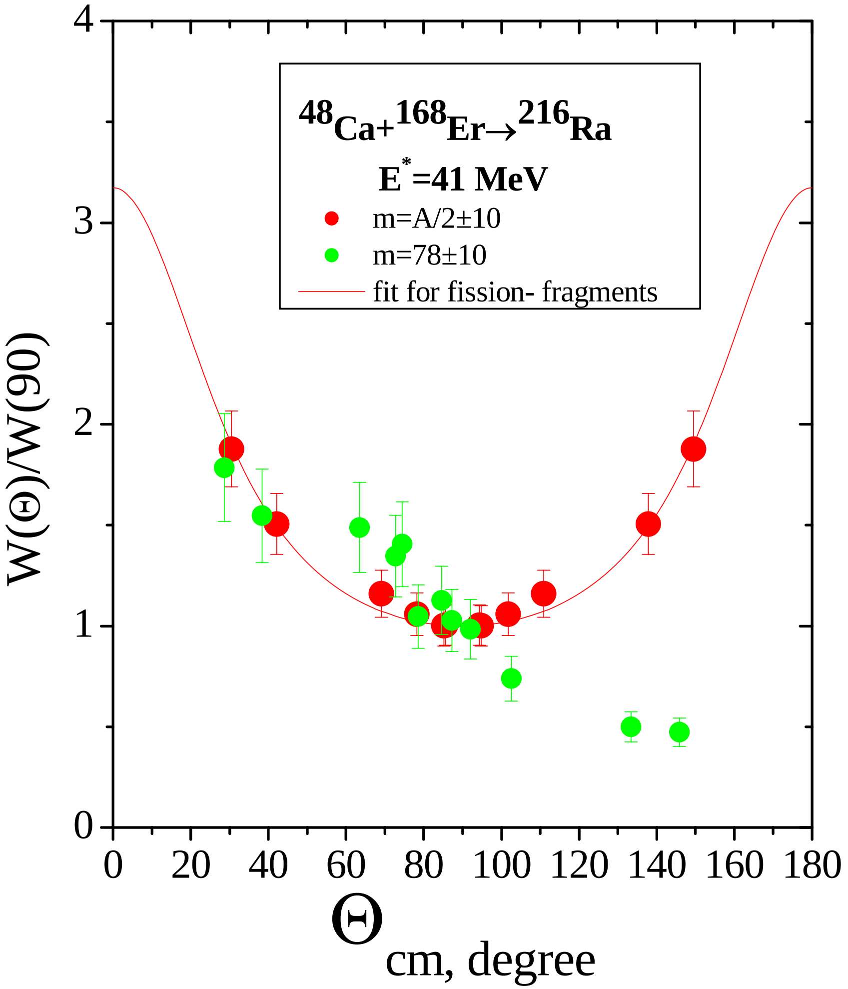
For example, at E* ≈ 40 MeV we found a percent contribution for the “shoulders” of:

≈1.5 % for ^{12}C+^{204}Pb

≈ 30 % for ^{48}Ca+^{168}Er

Two-dimensional TKE-Mass matrices and Mass yields for ^{216}Ra produced in the reactions with ^{12}C and ^{48}Ca projectiles

FF Angular distribution: $^{48}Ca+^{168}Er \rightarrow ^{216}Ra^*$



Fission fragments coming from equilibrated nuclei are symmetrically distributed around 90 degrees.

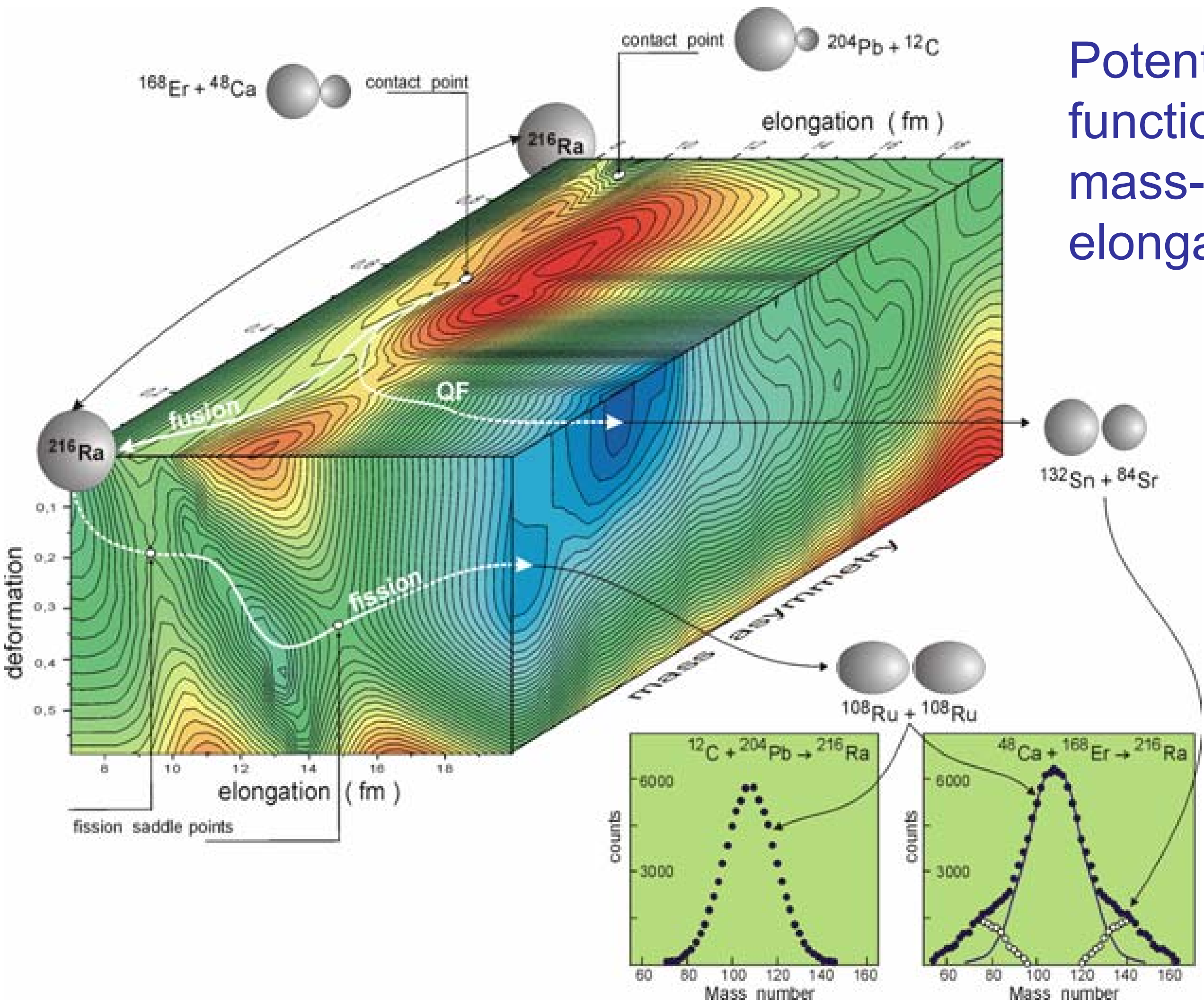
The angular distribution of mass-asymmetric FF presents a large anisotropy.

This anisotropy is evidence of the onset of the quasi-fission mechanism

(B.B. Back et al., PRC 32 (1985) 195)

M. Trotta et al., Prog. Theor. Phys. Suppl. 154 (2004) 37-44

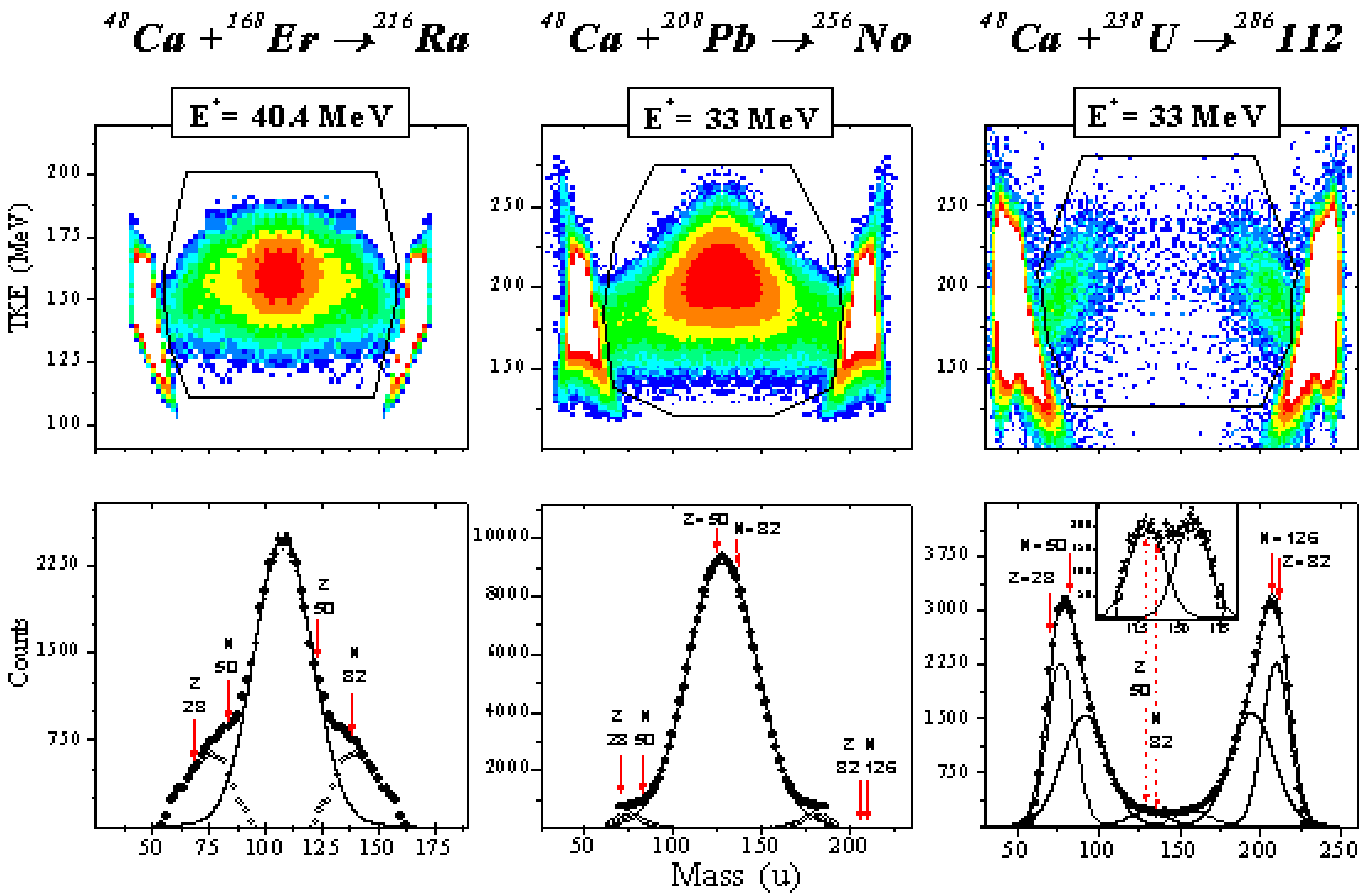
Entrance channel influence on fission dynamics



Potential energy surface as a function of the entrance channel mass-asymmetry, and of ^{216}Ra elongation and deformation

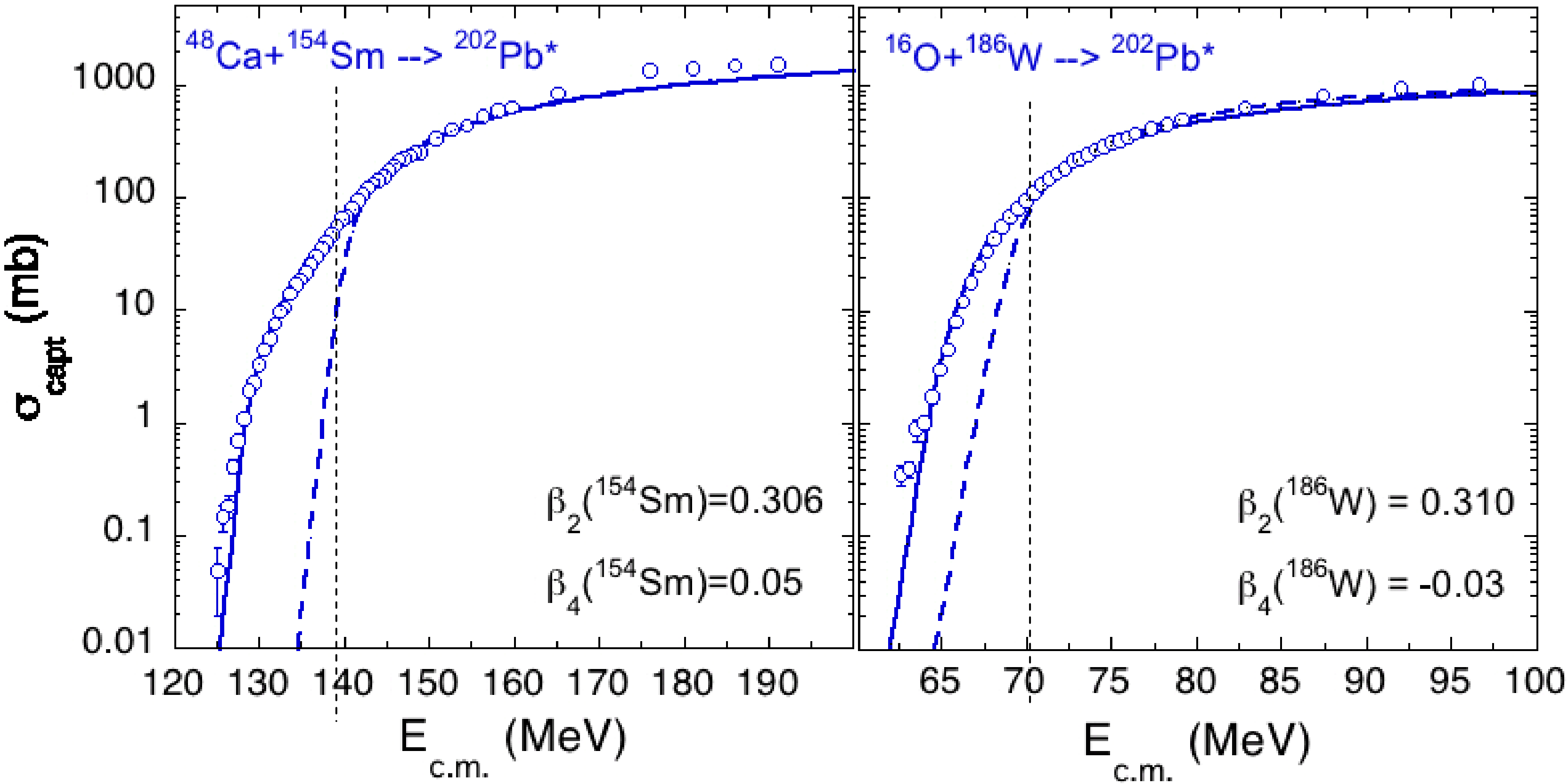
M.G.Itkis et al., Nucl.Phys. A734, 136 (2004); I.Pokrovsky et al., Phys. Atom. Nucl. 66, 1198 (2003)

Shell effects in fusion of heavy elements



M.G. Itkis et al., *Phys. Atomic Nuclei 66, 1118 (2003), Nucl. Phys. A 734, 136-147 (2004)*

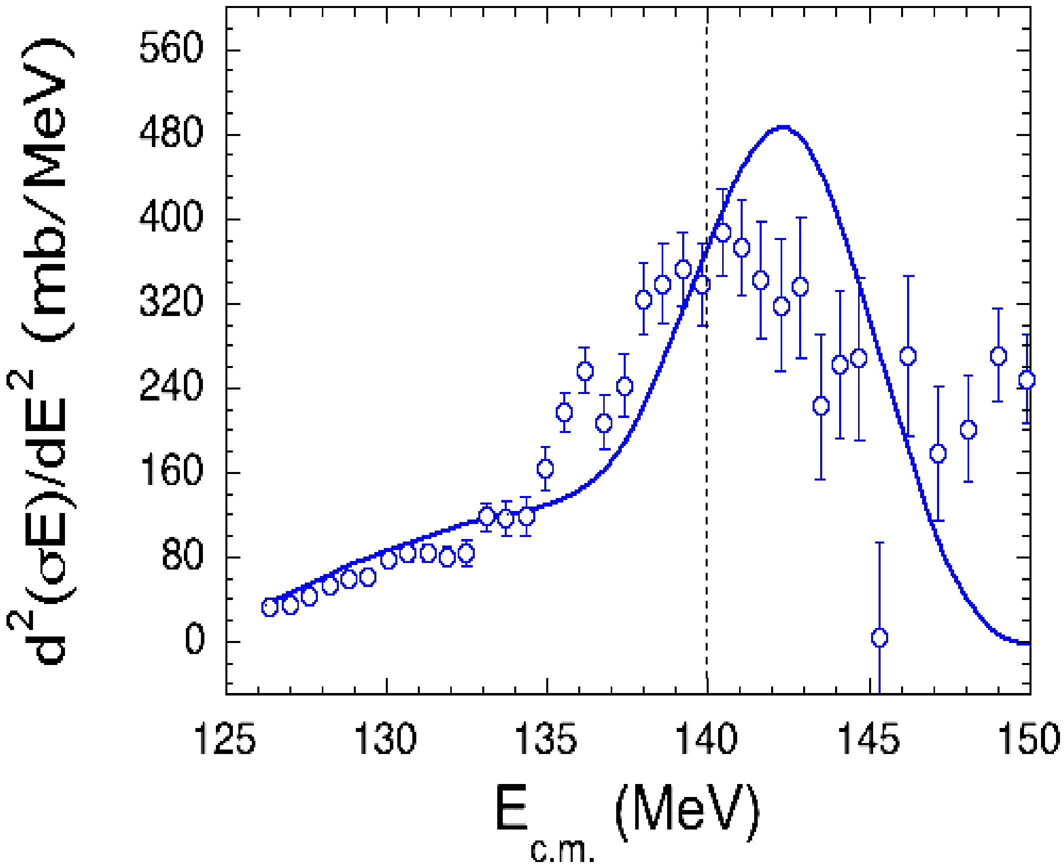
Capture cross sections and CC calculations : $^{202}Pb^*$



A good description of the capture cross sections is obtained in the Coupled-Channels approach for both reactions

M. Trotta et al., Eur. Phys. J. A25, s01, 615-618 (2005)

Barrier distribution (BD): $^{48}Ca+^{154}Sm$



Since systems with a wide BD result in large sub-barrier cross sections, it might be expected that reactions with nuclei which result in a wide BD will be ideal for forming heavy nuclei.

This deduction changes when the effect of entrance channel dynamics in the evolution to the compact configuration is considered.

Heavy projectiles on deformed targets lead to wide BD
(Coupling strenght $\propto \beta Z_P Z_T$)

A. M Stefanini, M. Trotta et al., Eur. Phys. J. A23, 473 (2005)

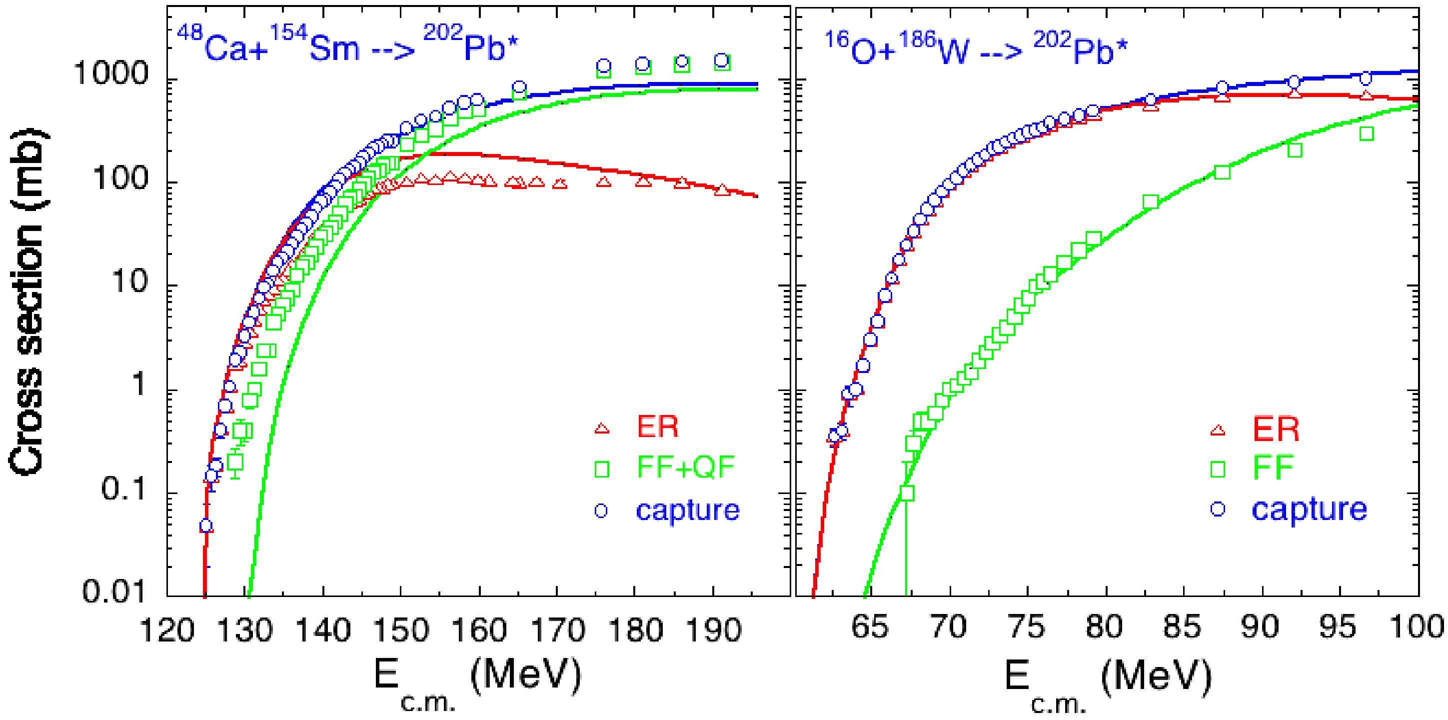
Cross sections and Statistical Model calculations: $^{202}Pb^*$

$$B_f(\ell) = k_f B_f^{LD}(\ell) - \delta W_{gs}$$

δW_{gs} = shell corrections as a difference between empirical g.s. masses and liquid drop (LD) masses

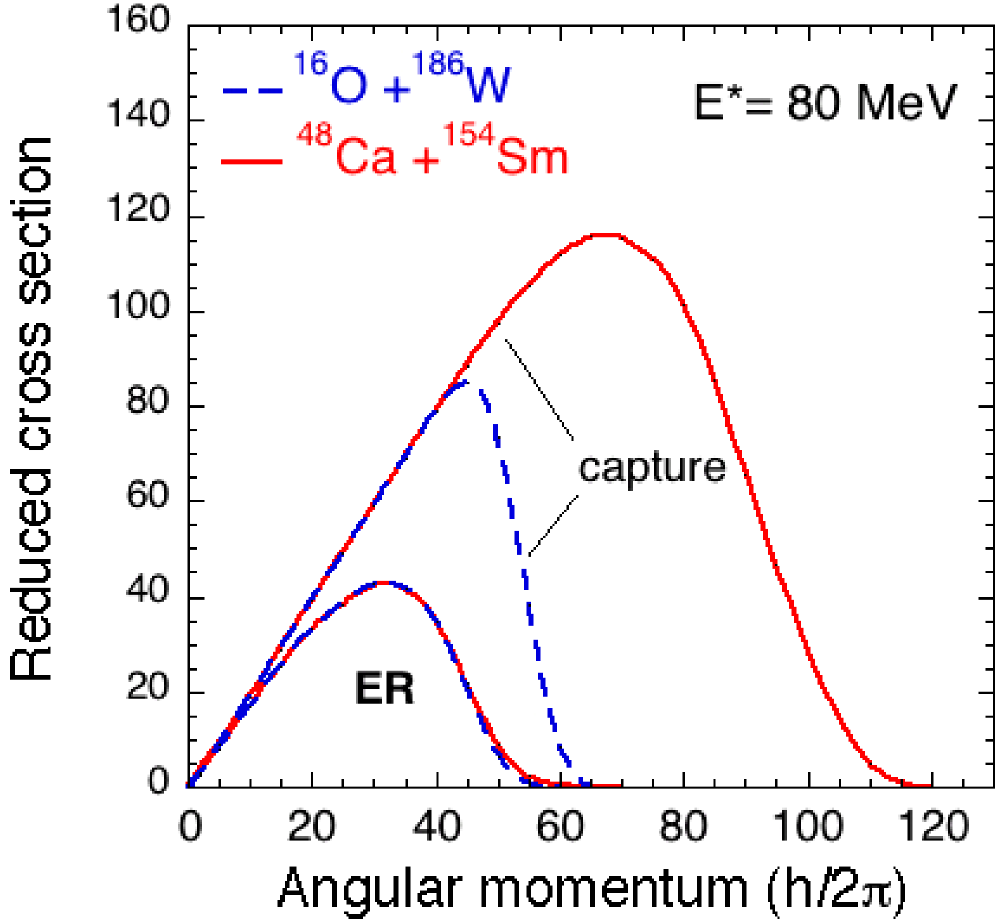
$\sigma(r_0)/r_0 =$ potential barrier fluct. generated with a gaussian distrib. of r_0 around its average fixed value

$k_f = 0.85 \quad \sigma(r_0)/r_0 = 5.3\%$ $\qquad$ $k_f = 0.85 \quad \sigma(r_0)/r_0 = 4.3\%$



ER cross sections are overestimated by statistical model calculations in the case of the $^{48}Ca+^{154}Sm$ reaction

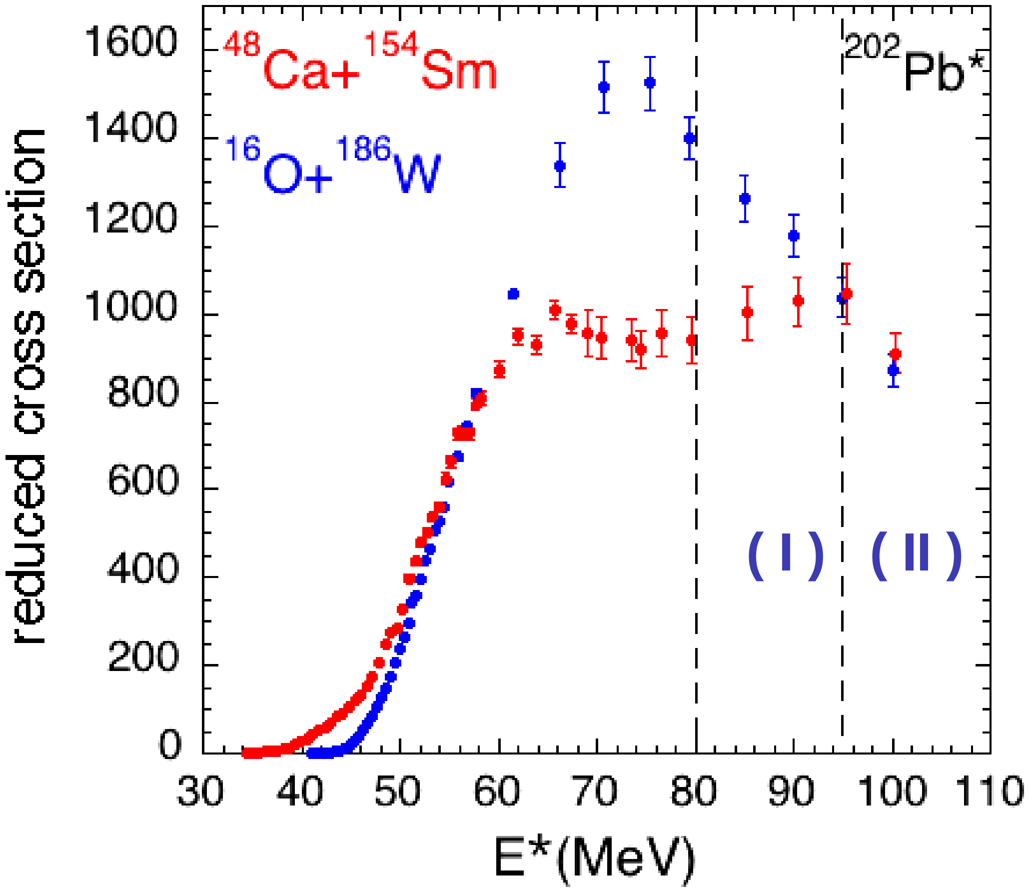
Statistical Model calculations (HIVAP) : $^{202}Pb^*$



Statistical model calculations show that at $E^* \geq 80$ MeV the capture probabilities T_l are close to unity for all the low angular momenta contributing to ER production.

At this excitation energy the two reactions should give the same ER reduced cross sections.

Fusion hindrance in ^{48}Ca + ^{154}Sm

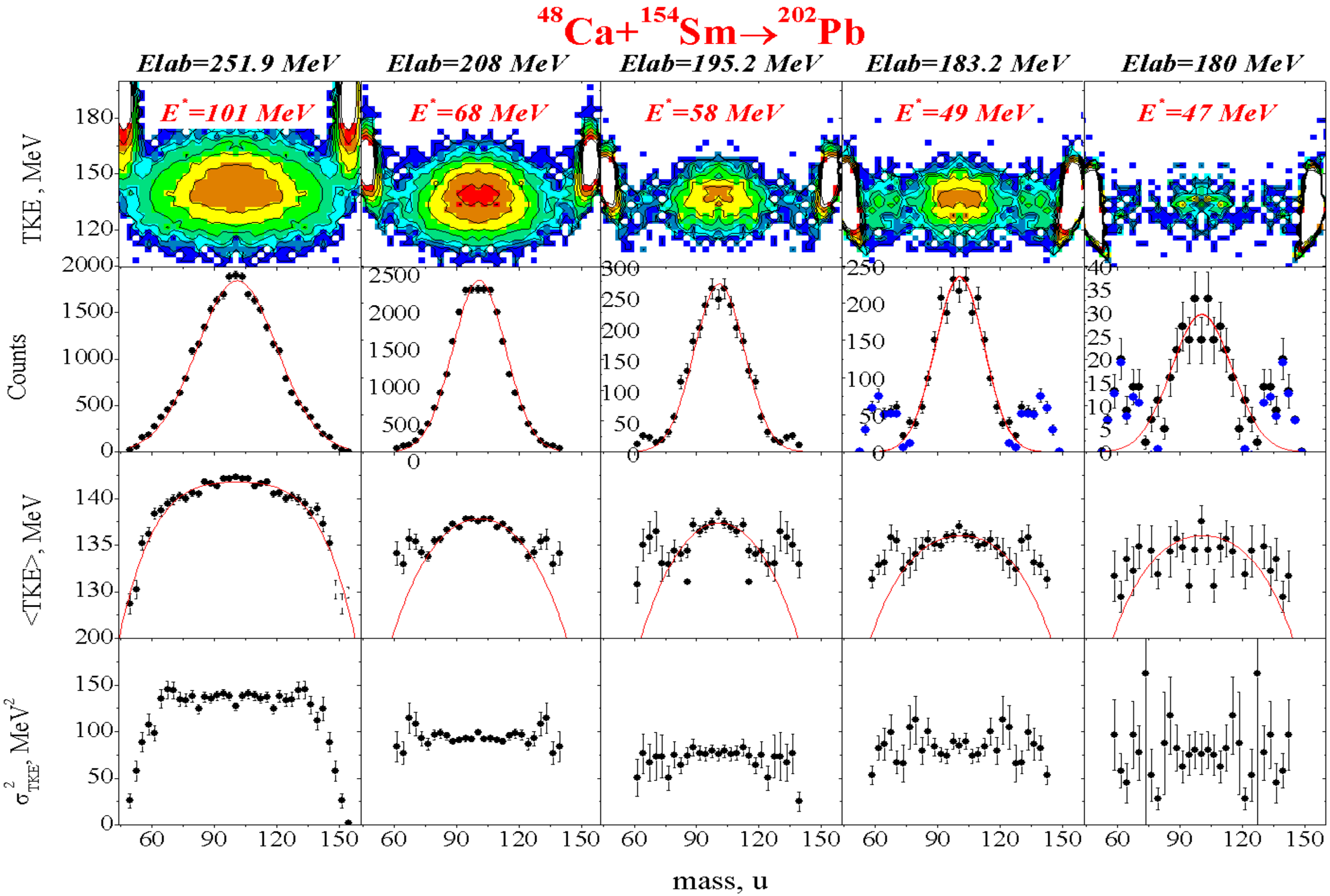


I. E*=80-95 MeV
Fusion is strongly suppressed for the ^{48}Ca induced reaction in a region where similar ER reduced cross sections are expected (onset of QF)

II. E*=95-100 MeV
Possible emission of pre-equilibrium charged particles or disappearance of fusion hindrance?

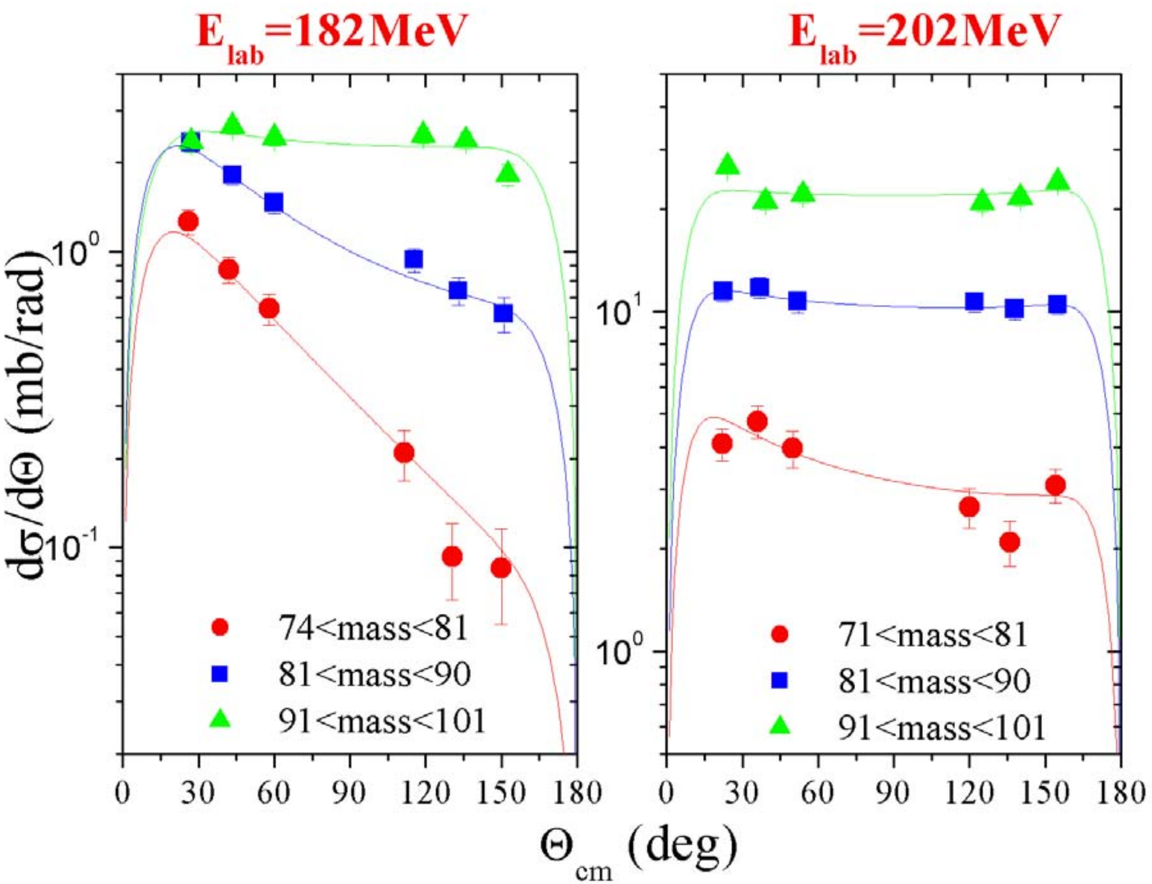
QF competes with complete fusion at high energies even at the low angular momenta leading to ER survival

FF Mass-Energy distribution: $^{48}Ca + ^{154}Sm \rightarrow ^{202}Pb^*$



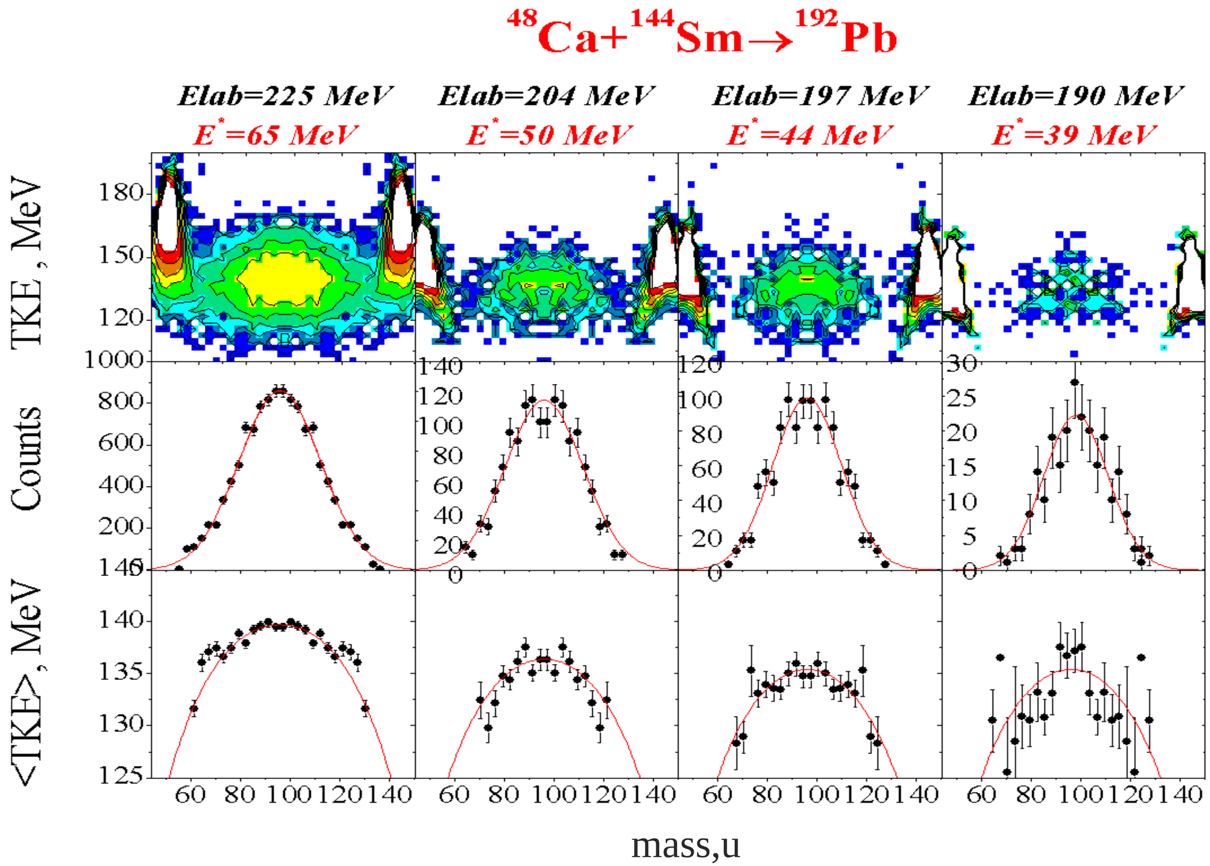
The relative yield of the asymmetric component increases with the decreasing E*

FF Angular distribution: $^{48}Ca+^{154}Sm \rightarrow ^{202}Pb^*$



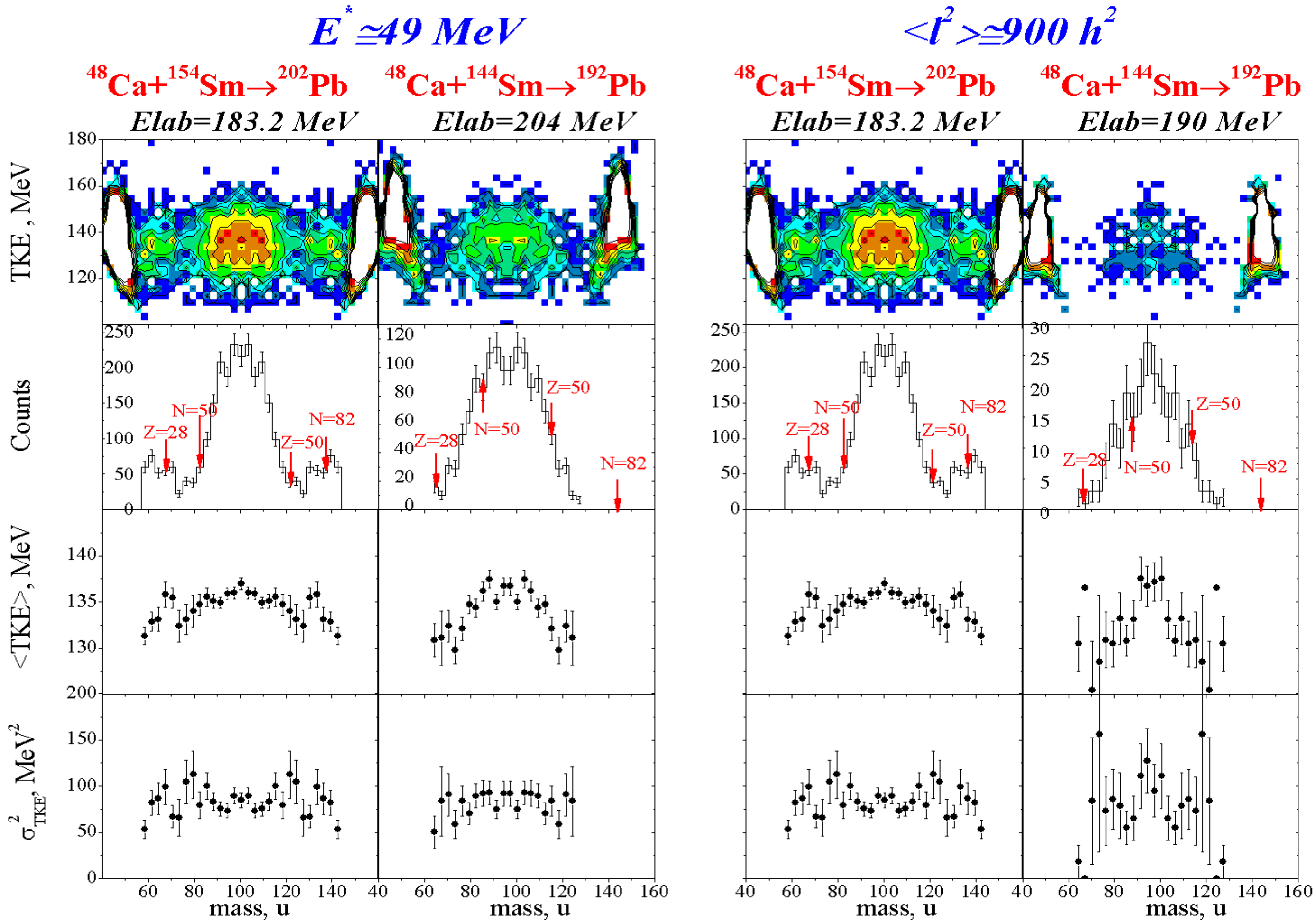
Angular distributions obtained in the ^{48}Ca+ ^{154}Sm reaction for fission-like fragments corresponding to the selected fragment mass bins.

FF Mass-Energy distribution: $^{48}Ca + ^{144}Sm \rightarrow ^{192}Pb^*$



No evidence of asymmetric fission/QF in $^{48}Ca + ^{144}Sm$

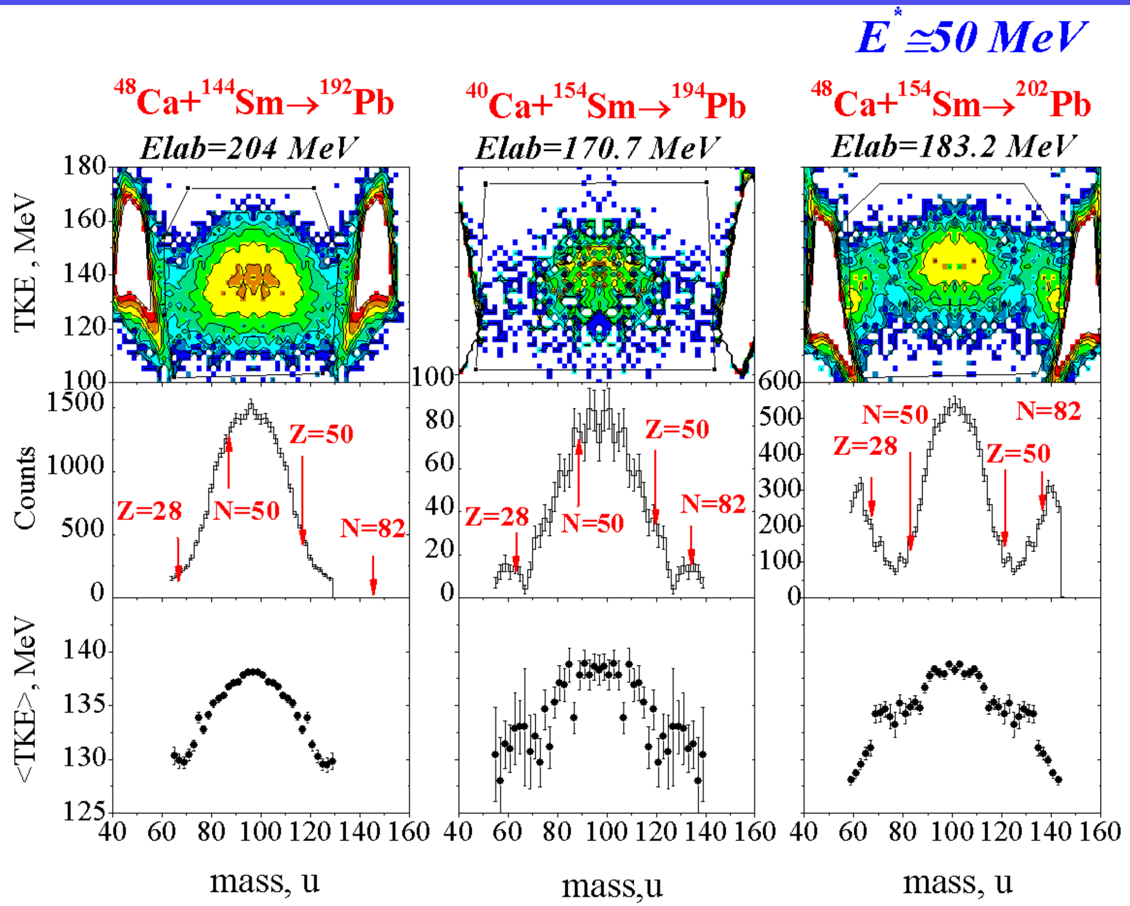
The effect of target deformation on quasi-fission



Target deformation: ^{144}Sm: β_2=0, β_4=0 ^{154}Sm: β_2=0.27, β_4=0.113

No evidence of asymmetric fission/QF in ^{48}Ca+ ^{144}Sm

The effect of target deformation on quasi-fission

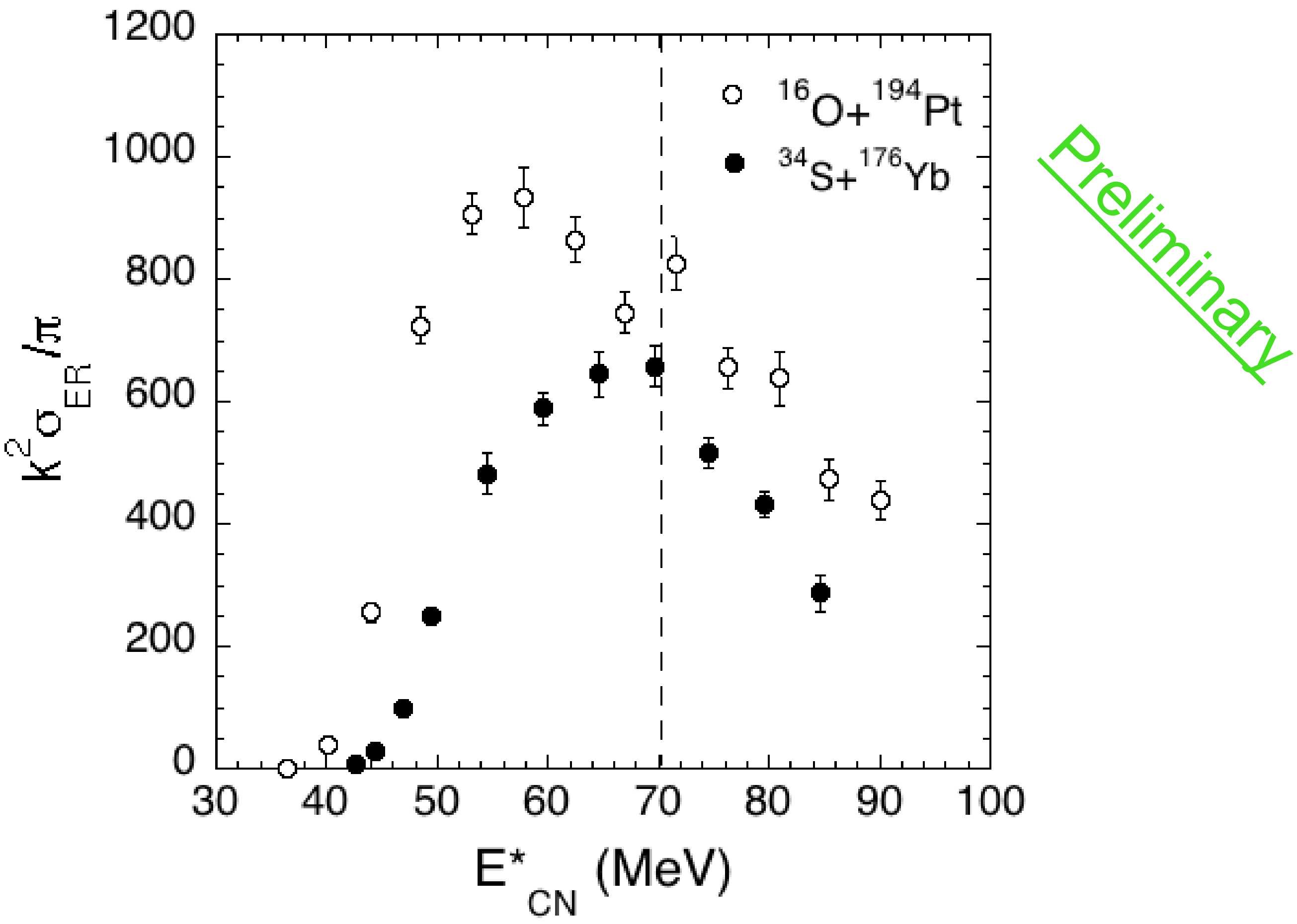


Target deformation: ${}^{144}Sm$: $\beta_2=0$, $\beta_4=0$ ${}^{154}Sm$: $\beta_2=0.27$, $\beta_4=0.113$

The target deformation favours the onset of asymmetric fission/QF

M. Trotta et al., Eur. Phys. J. A25, s01, 615-618 (2005)

$^{210}Rn^*$: fusion hindrance from E-ToF measurements



Data analysis is in progress to extract absolute cross sections for individual ER's from the yields of characteristic alpha particles emitted

Conclusions

- Mass asymmetry: more symmetric systems lead to a large fusion hindrance also in a relatively light CN such as $^{202}Pb^*$ for high E^* even at the low angular momenta populating ERs

- Shell effects: seem to play a role in the onset of QF

- Target deformation: deformed targets lead to wide barrier distributions, but the target deformation favours the onset of QF

Collaboration

INFN-LNL (Italy): A.M. Stefanini, L. Corradi, B.R. Behera, E. Fioretto, A. Gadea, A. Latina, S. Szilner

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