Probing quasifission in reactions forming Rn nucleus

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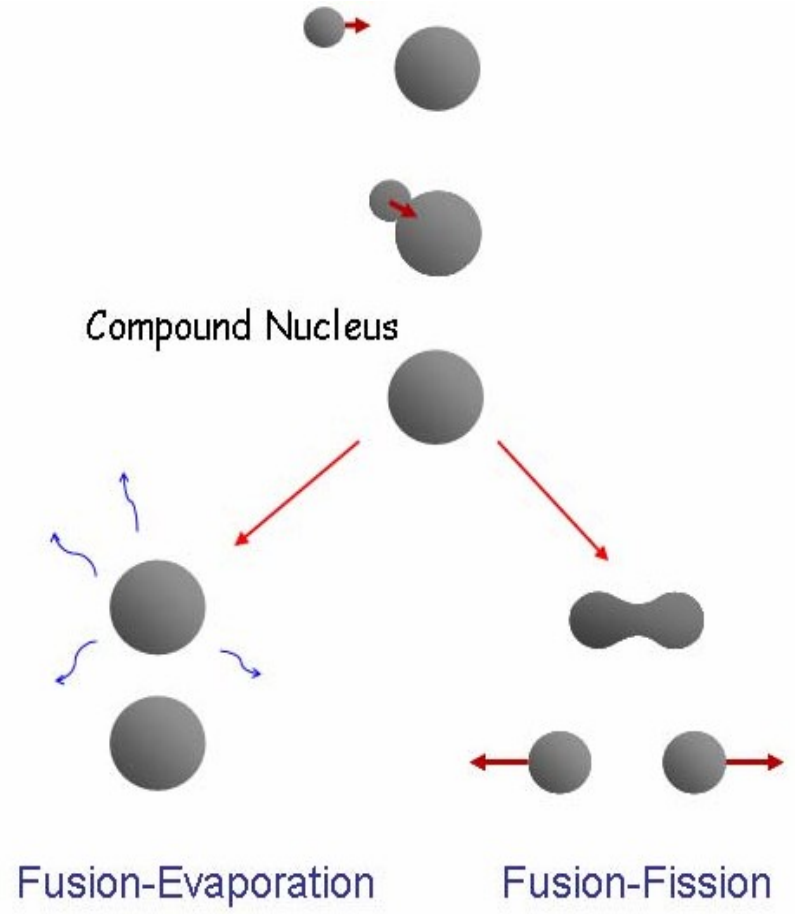
Outline

- Introduction
- Our goals
- Experimental details
- Results & Discussion
- Conclusion

Heavy-ion fusion-fission reactions

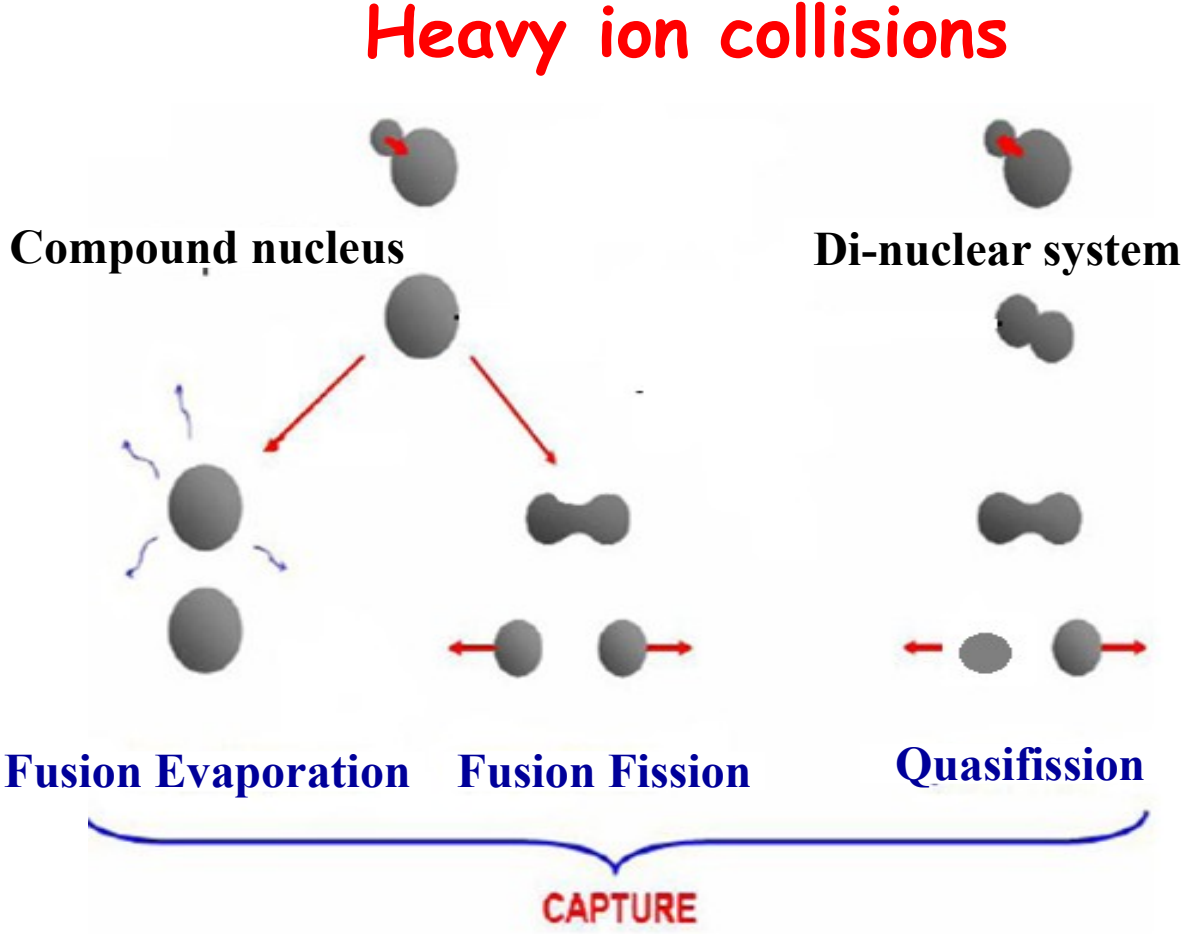
- Overcoming the Coulomb barrier
- Formation of an equilibrated compound nucleus (CN)
- Statistical decay of the CN
  - Evaporation
  - Fission



Heavy-ion fusion-fission reactions

◆ Overcoming the barrier does not guarantee fusion always !!!

◆ Strong **hindrance to fusion** by **Non-CN** process called **Quasifission (QF)**



Heavy-ion fusion-fission reactions

- Factors affecting FF/QF
  - Excitation energy
  - Angular momentum
  - Entrance channel mass asymmetry,
    $\alpha = (A_T - A_P)/(A_P+A_T)$
  - Nucleus deformation and orientation
  - $Z_P Z_T$

Experimental Probes to study QF

- Study of fission fragment angular distribution

  Large angular anisotropy for QF

- Fission fragment mass - angle distributions

  Mass-angle correlations

- Fission fragment mass distribution

  Broader FF Mass Ratio Distributions

- Study of evaporation residue (ER)

  Lower ER yields for QF

Our goals

- Studying the onset of the QF mechanism
- Entrance channel dependence of fusion-fission and QF competition

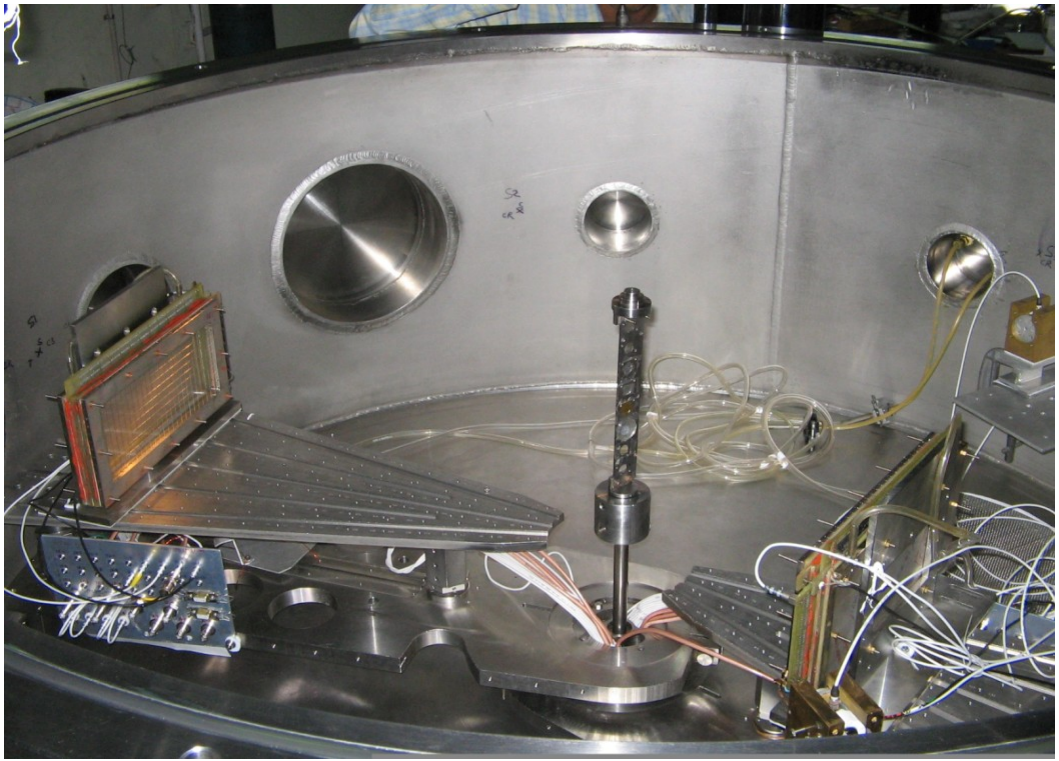
Systems	Excitation energy range
$^{210}Rn \rightarrow {}^{16}O + {}^{194}Pt$	$E^* \rightarrow 40 - 65$ MeV
$^{30}Si + {}^{180}Hf$	$E^* \rightarrow 47 - 82$ MeV
$^{208}Rn \rightarrow {}^{28}Si + {}^{180}Hf$	$E^* \rightarrow 51 - 106$ MeV

Observables

- FF mass-angle and mass ratio distributions.
- ER cross-sections.

FF mass distribution measurements

- $^{30}Si + {}^{180}Hf \rightarrow {}^{210}Rn$
- General Purpose Scattering Chamber (GPSC)
- Multi Wire Proportional Counters (MWPC)
- Position and timing information
- Collection and Analysis of Nuclear Data using Linux nEtwork (CANDLE)

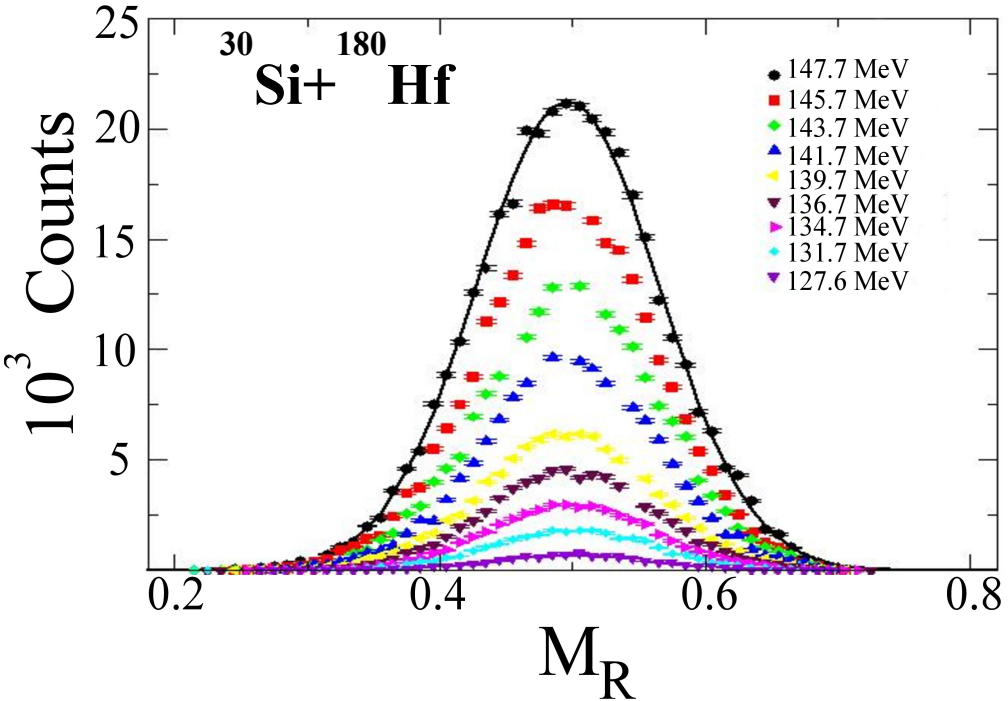


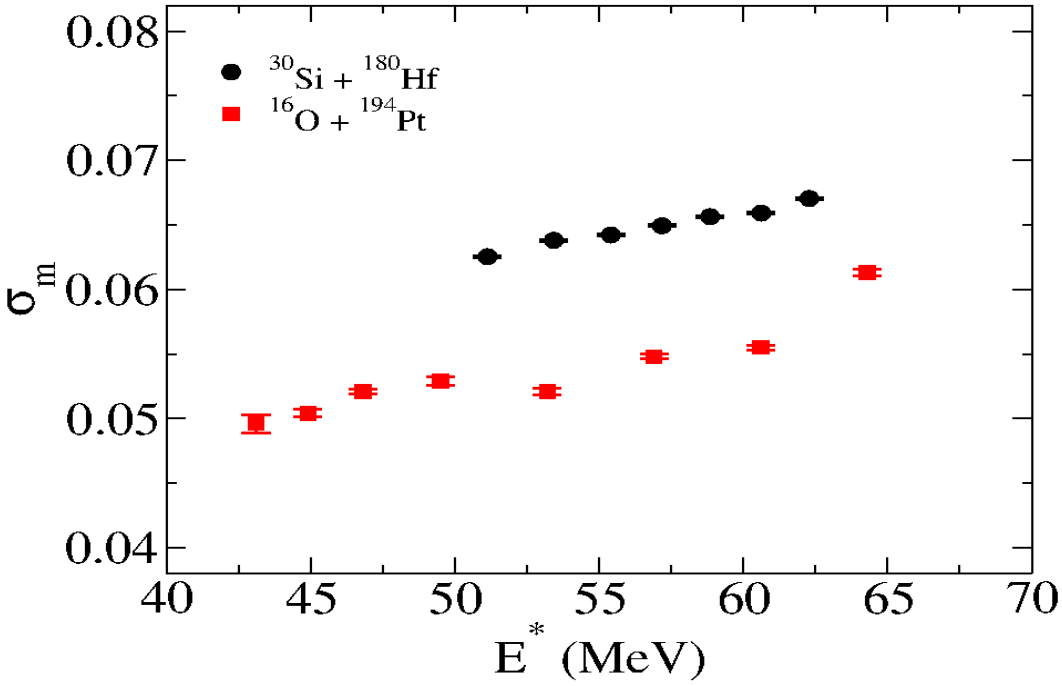
GPSC

FF mass ratio distribution studies

$$M_R = \frac{m_1}{m_1 + m_2}$$

Experimental mass ratio widths of the fragments from the ^{16}O+ ^{194}Pt & ^{30}Si+ ^{180}Hf reactions.

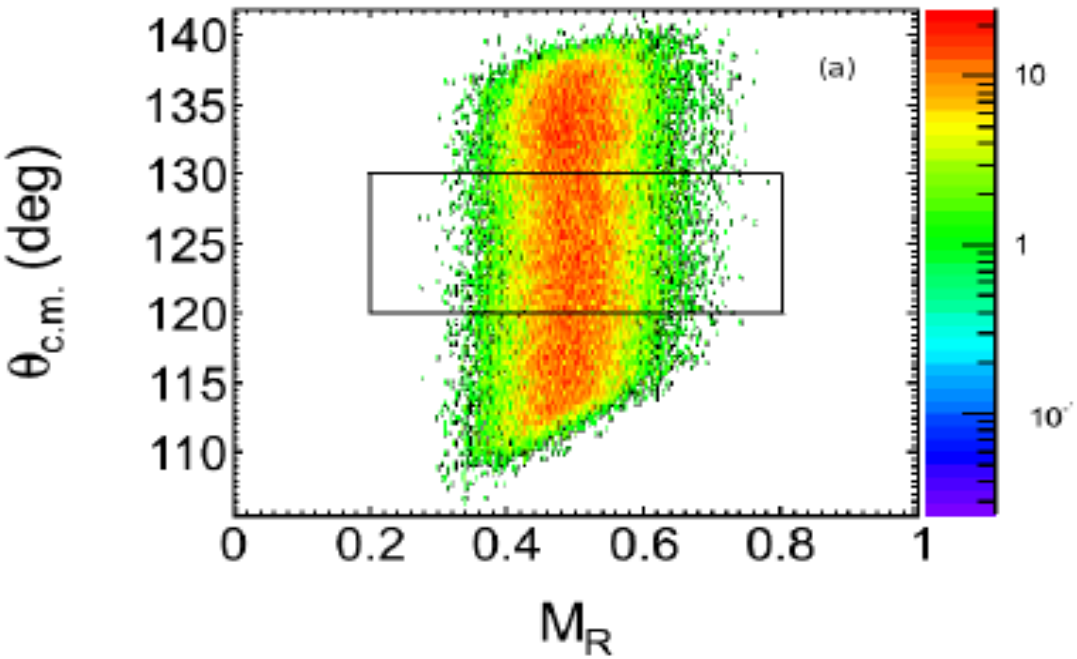




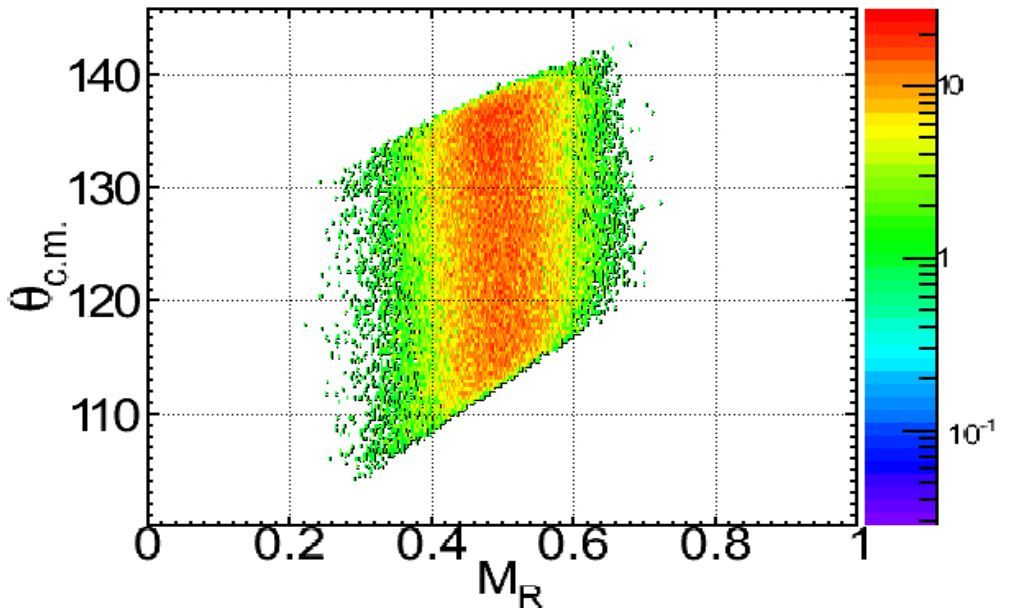
E. Prasad et al., Phys. Rev. C 81, 054608 (2010), A. Shamlath et al., Nucl. Phys. A 945, 67 (2016).

FF mass-angle distributions (MAD)

$^{16}O+^{194}Pt$



$^{30}Si+^{180}Hf$



No mass-angle correlation

For completely fused system

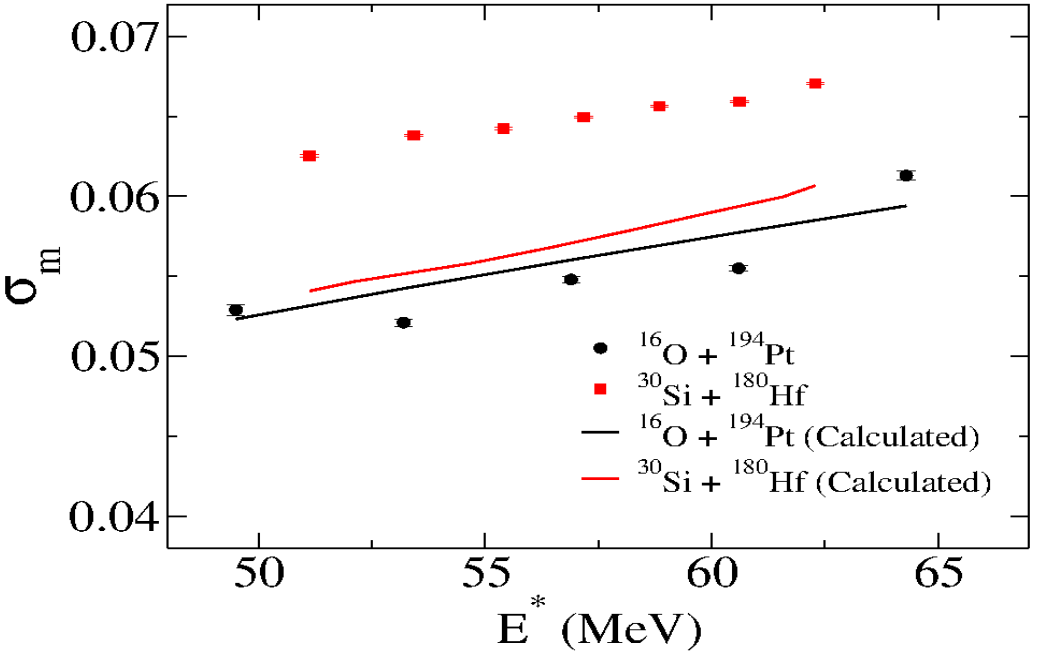
$$\sigma_m^2 = \lambda T + \kappa \langle l^2 \rangle$$

Saddle point Model

$$E_x^{sad} = E_x - B_f - E_{pre}^{sad} - E_{rot}^{sad}$$

$$T = \sqrt{\frac{E_x^{sad}}{a}}$$

Experimental mass ratio widths for the $^{30}Si + ^{180}Hf$ and $^{16}O + ^{194}Pt$ systems (solid points) compared with the calculations assuming saddle point model (solid lines).



Scission point Model

$$E_x^{sci} = E_x + Q_{sym} - T_{KE} - E_{pre}^{sci} - E_{rot}^{sci} - E_{defm}$$

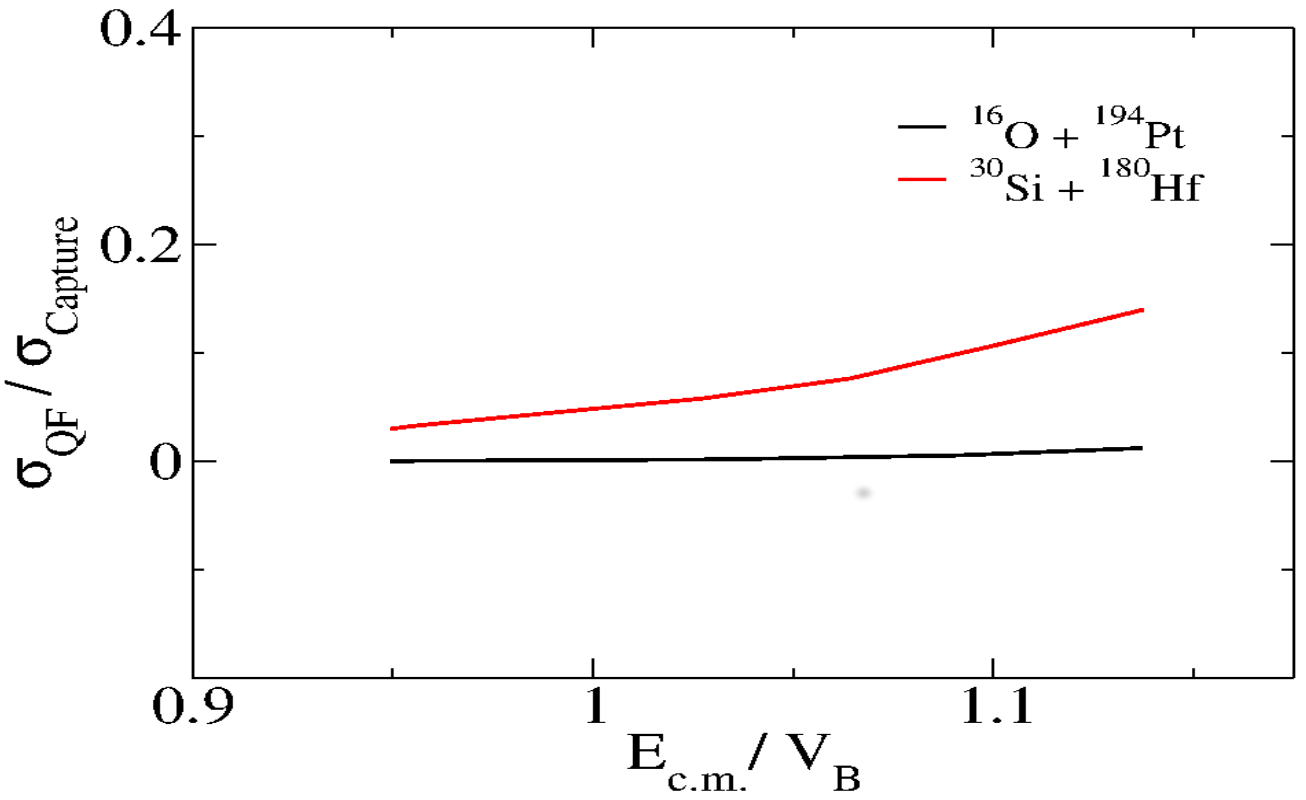
$$T = \sqrt{\frac{E_x^{sci}}{a}}$$

Di-nuclear system (DNS) model calculation

- Theoretical approach to describe and predict the capture, fusion and QF cross sections.
- Interaction with different orientation angles of the deformed nuclei is considered.
- Dependence of barrier on the energy and angular momentum.
- $\sigma_{cap} = \sigma_{Fusion}\ (\sigma_{ER} + \sigma_{FF}) + \sigma_{QF}$

A.K. Nasirov et al., Eur. Phys. J. A 49 (2013) 147.

Di-nuclear system (DNS) model calculation



Significant QF probability – $^{30}Si+^{180}Hf$ reaction

Observations

- No mass angle correlation.
- The width of the mass ratio distribution increases with an increase in excitation energy.
- At similar excitation energies, the magnitude of σ_m values for the $^{30}Si + ^{180}Hf$ reaction is much higher than that of the $^{16}O + ^{194}Pt$ reaction, forming the same CN ^{210}Rn.
- These observations confirms the presence of Quasifission in $^{30}Si + ^{180}Hf$ reaction.

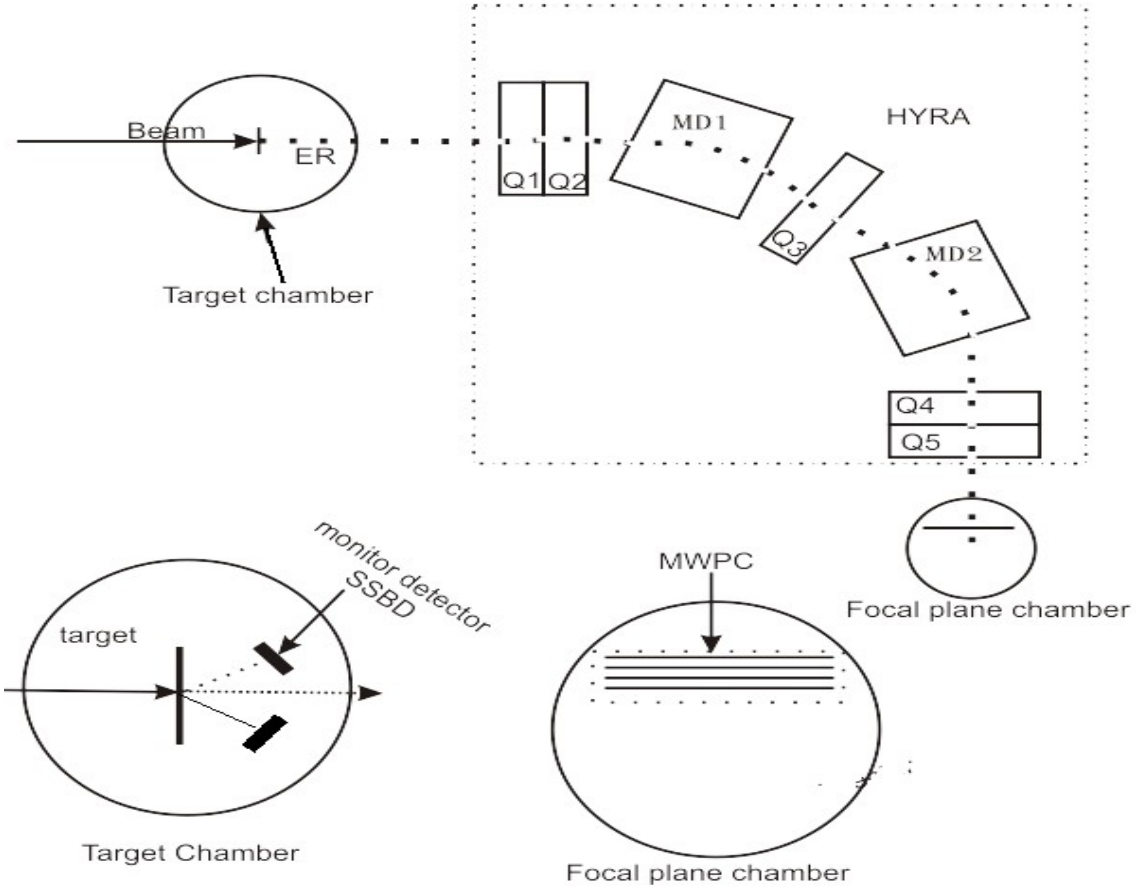
Entrance channel dependence

➡ ER measurements

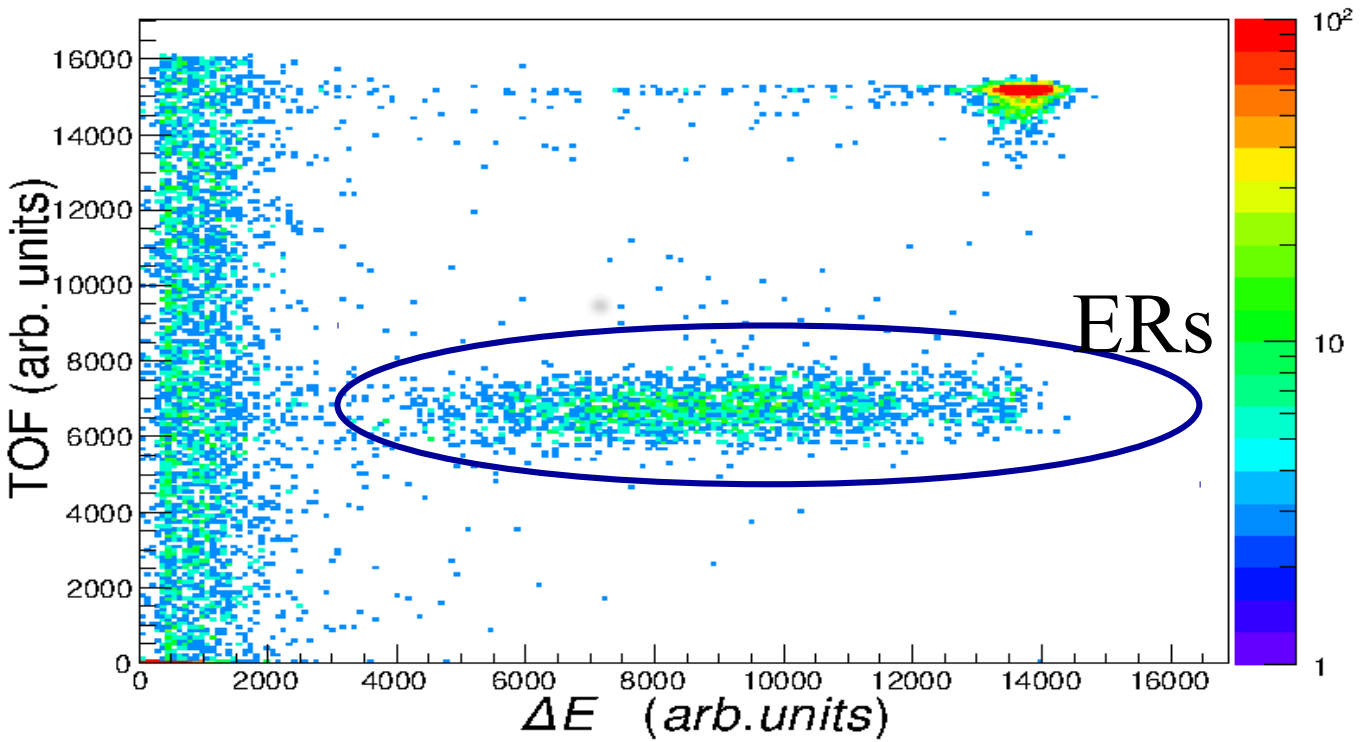
Experimental Details

HYbrid Recoil mass Analyzer (HYRA) in gas-filled mode

- Unique dual-mode, dual-stage spectrometer
- Gas-Filled Mode: First stage
- MWPC
- Energy, positions and time are recorded for the decay products
- TOF detectors help discriminating between ER and beam- and target-like contaminations



ΔE-TOF Spectrum



- The energy loss (ΔE) vs TOF spectrum helped in unambiguous identification of ERs from the beam-like and the target-like contaminations.

ER cross section

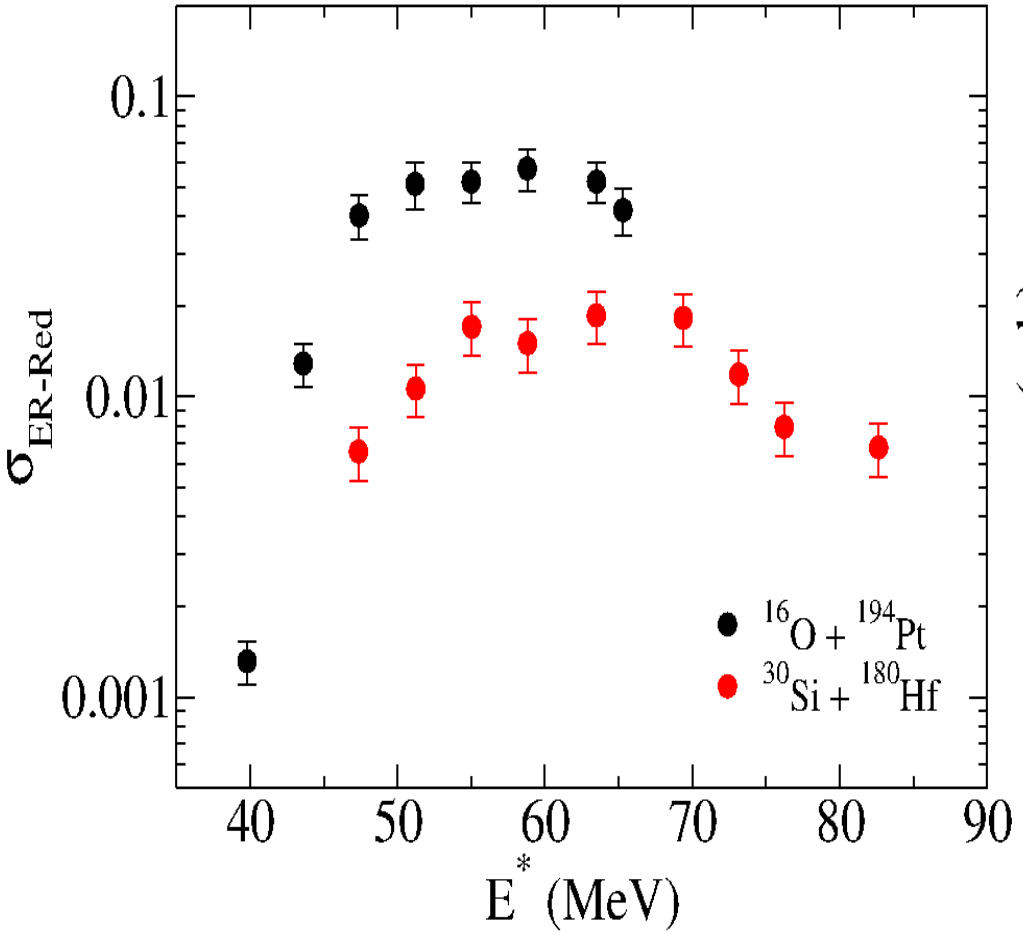
$$\sigma_{ER} = \frac{Y_{ER}}{Y_{mon}} \left(\frac{d\sigma}{d\Omega} \right)_R \Omega_M \frac{1}{\varepsilon_{HYRA}}$$

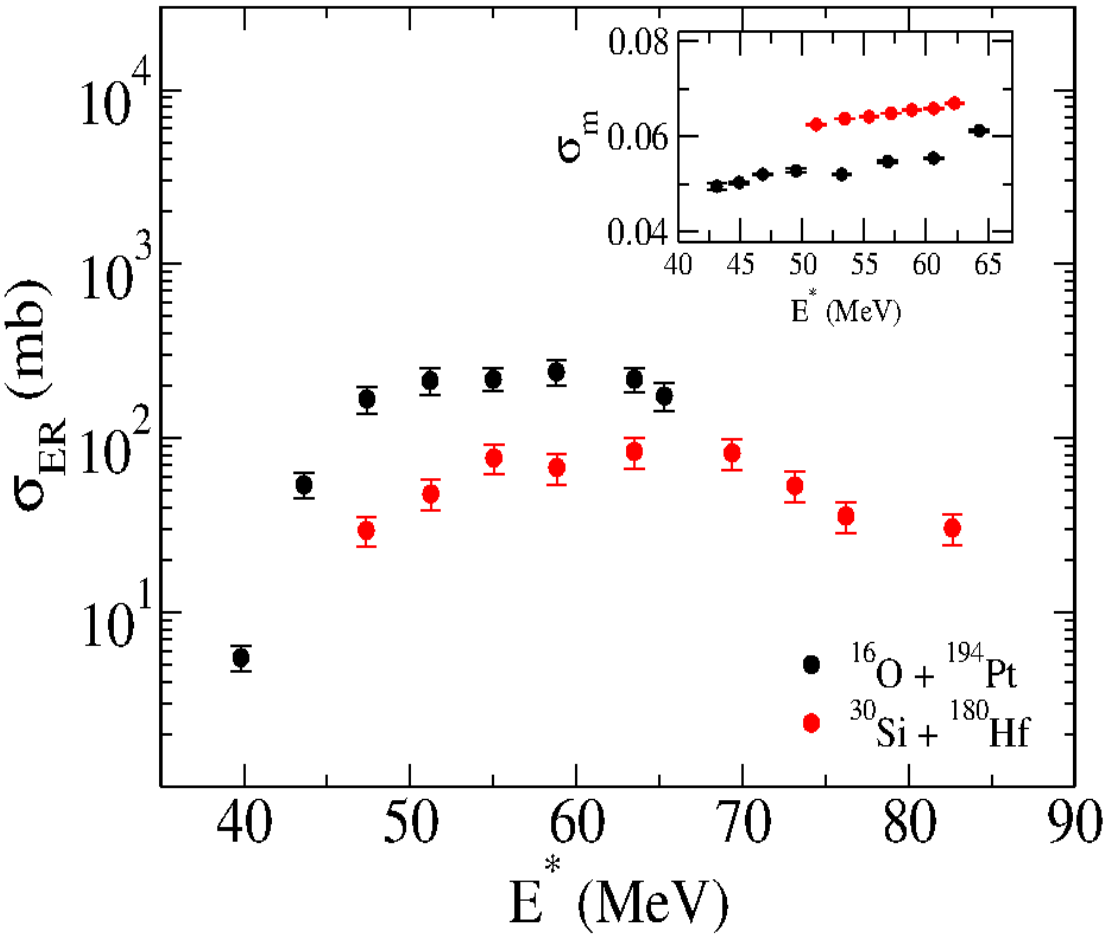
- σ_{ER} → ER cross section
- Y_{ER} → ER yield at the focal plane
- Y_{mon} → Yield in the monitor detector
- Ω_M → Solid angle subtended by the monitor detector
- $(d\sigma/d\Omega)_R$ → Differential Rutherford scattering cross section in the laboratory system.
- ε_{HYRA} → HYRA transmission efficiency

  Calibration system - $^{30}Si + ^{186}W$

A.C. Berriman et al.,Nature (London) 413 (2001) 144, D. J. Hinde et al., J. Nucl. Radiochem. Sci. 3, 31 (2002).

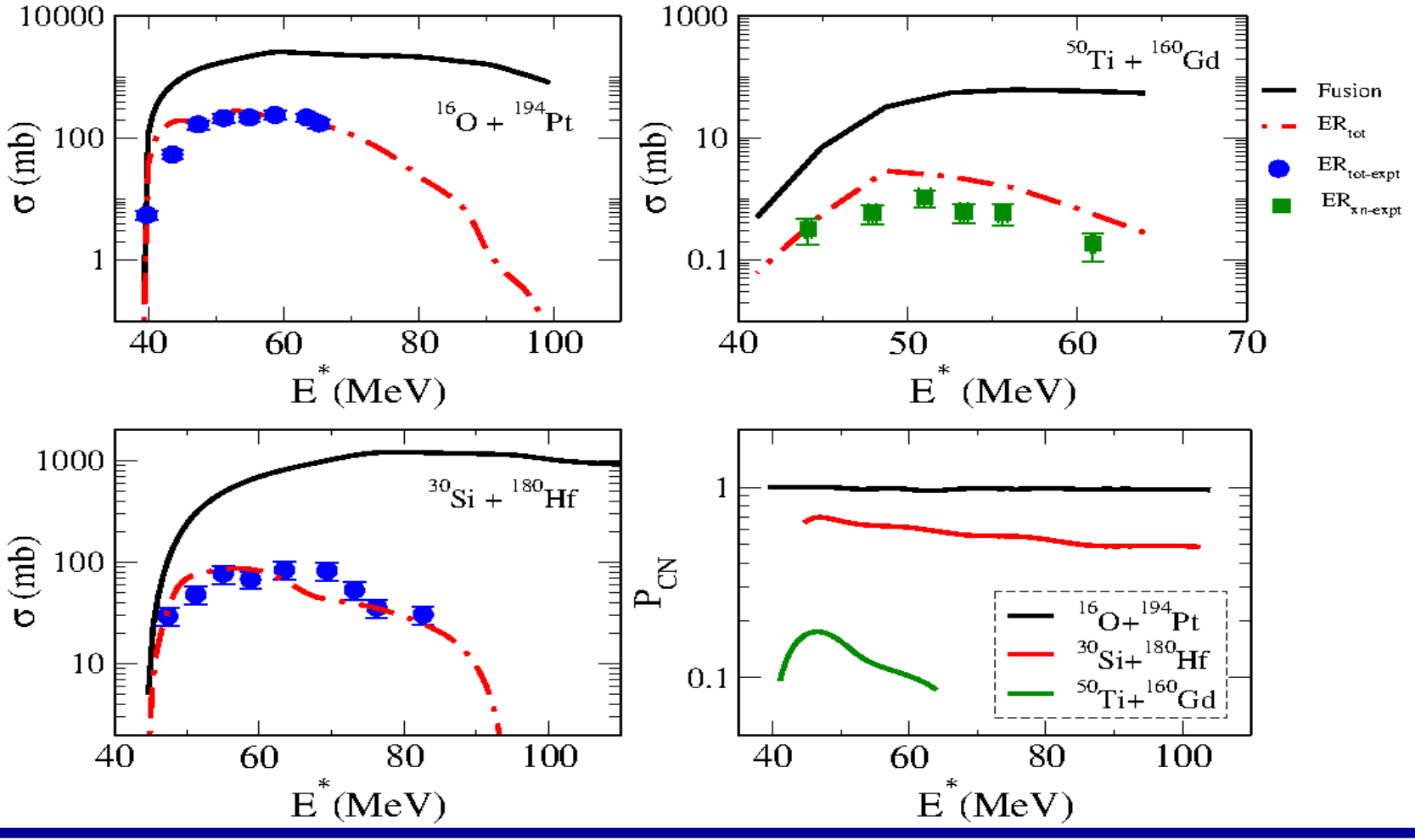
ER Cross Section-Reactions forming ^{210}Rn CN





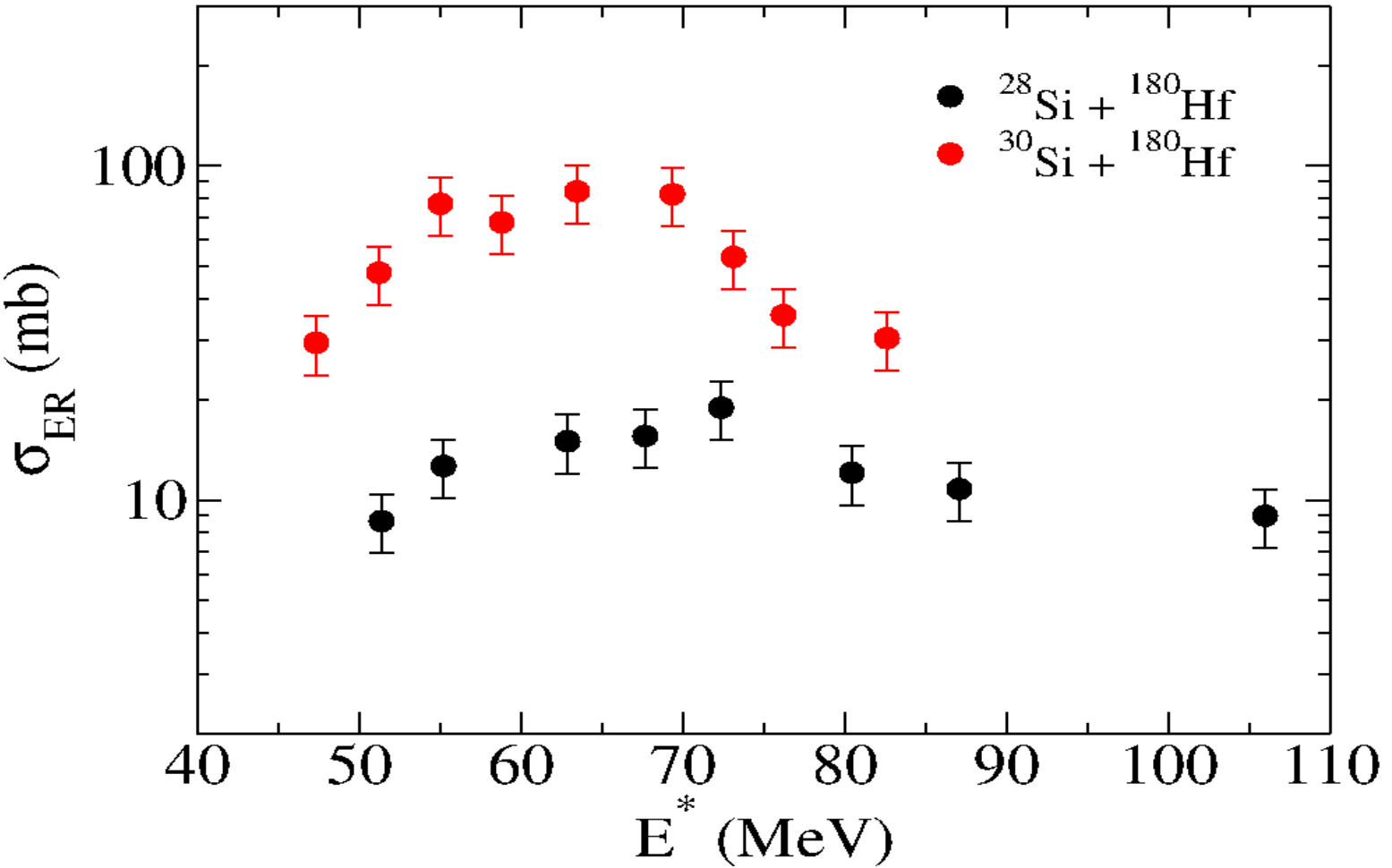
E. Prasad et al., Phys. Rev. C. 84, 064606 (2011).

DNS Results

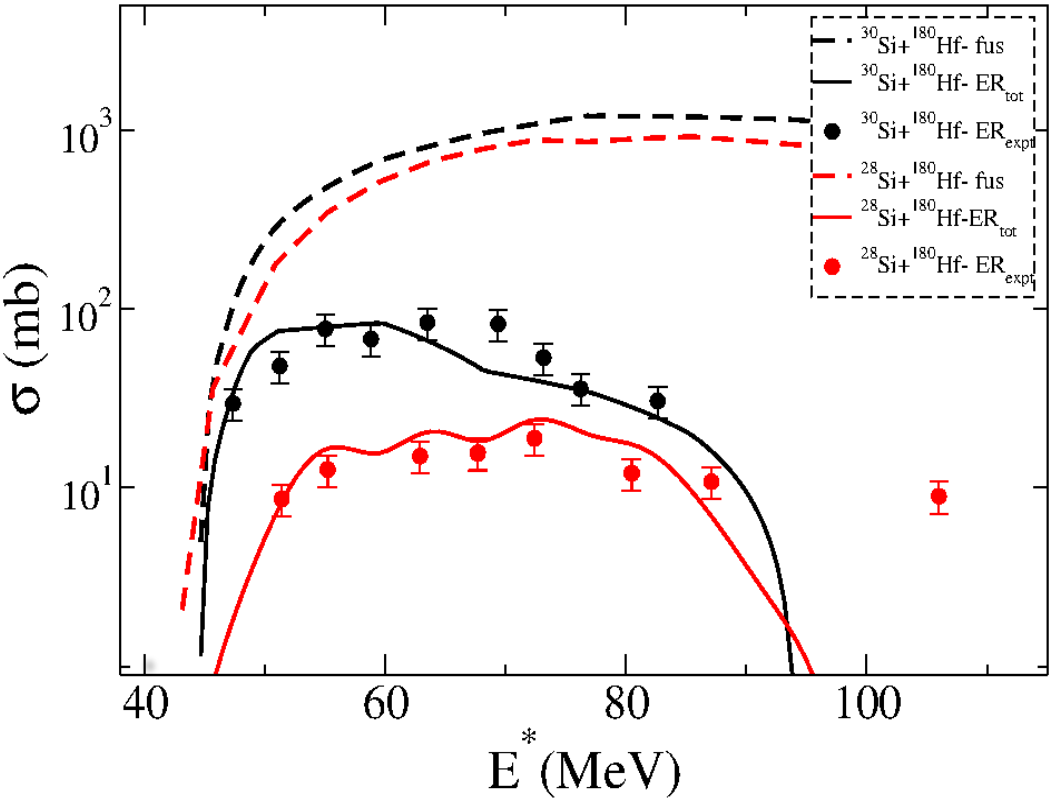


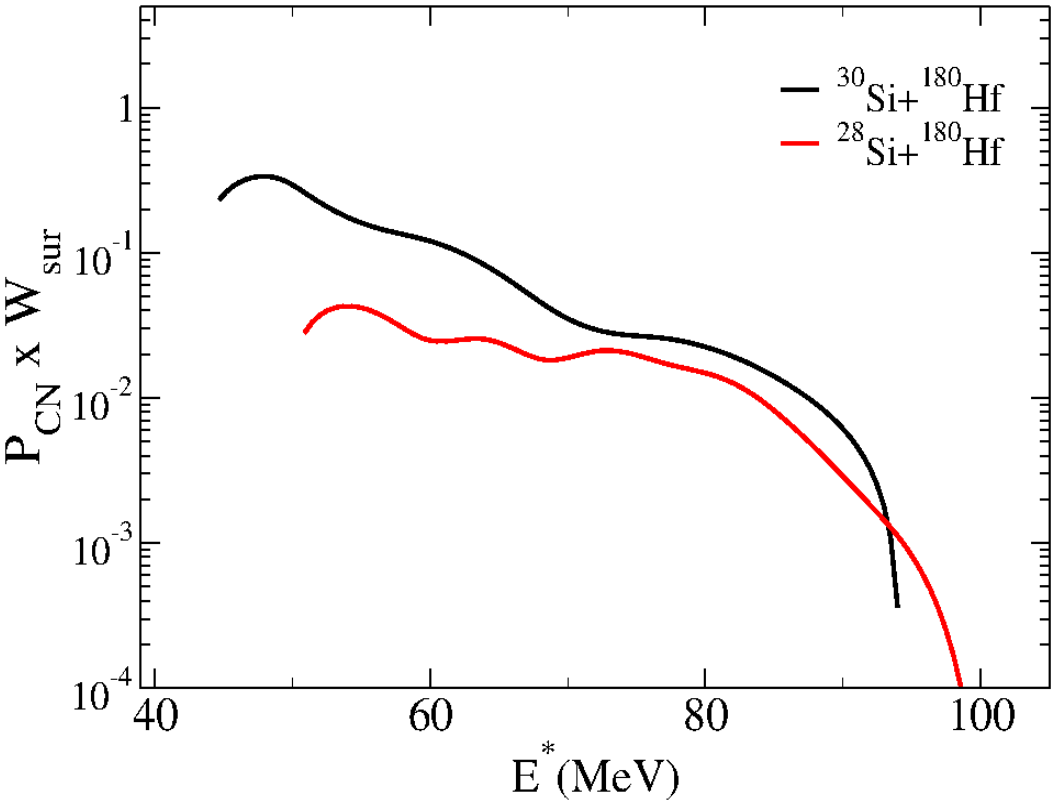
D. A. Mayorov et al., Phys. Rev. C. 92, 054601 (2015).

ER Cross Section $^{28,30}Si+^{180}Hf$



DNS Results





- The model analysis are in agreement with the experimental observations
- Clear signature of QF process in ^{28,30}Si + ^{180}Hf reactions

To be published

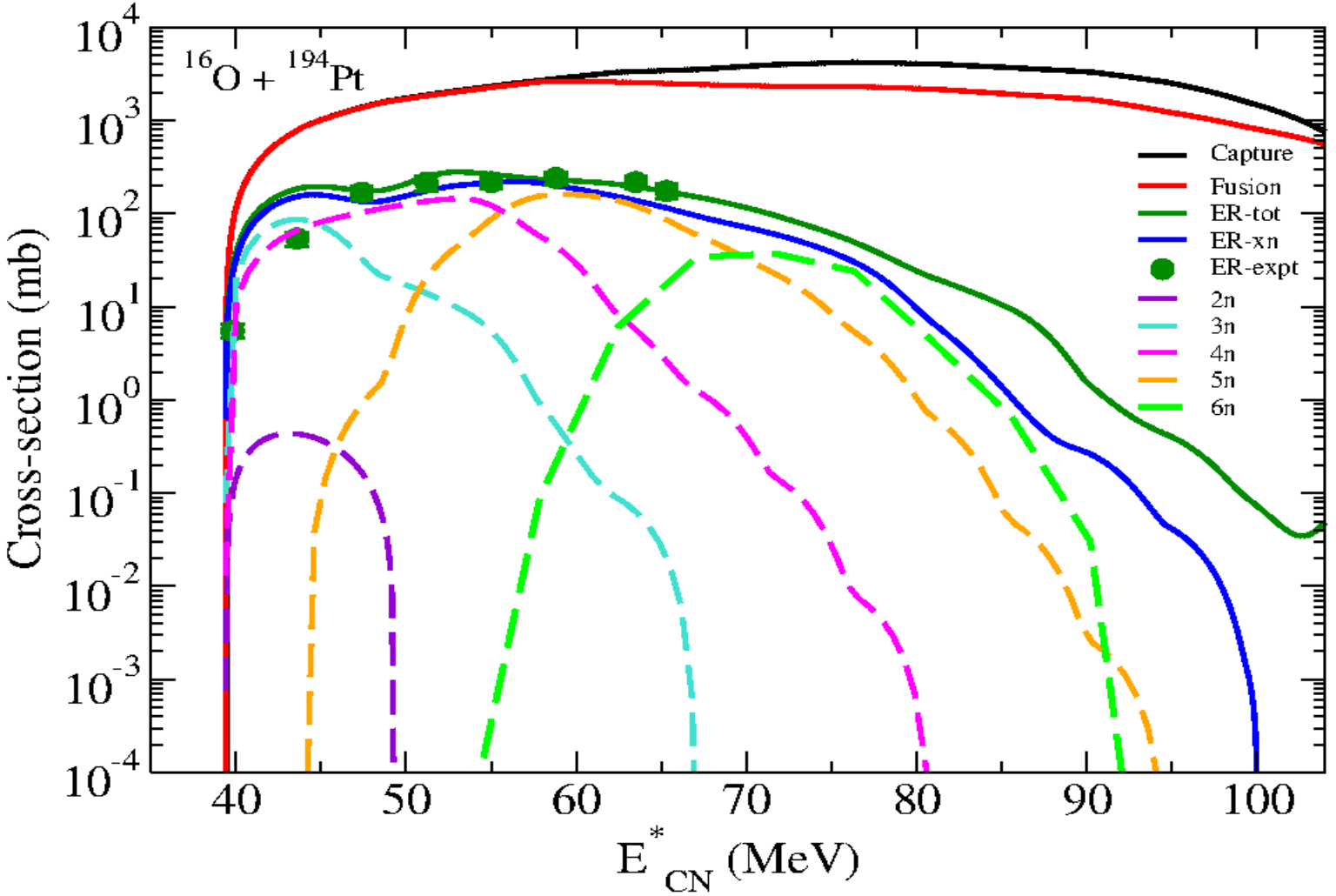
Conclusions

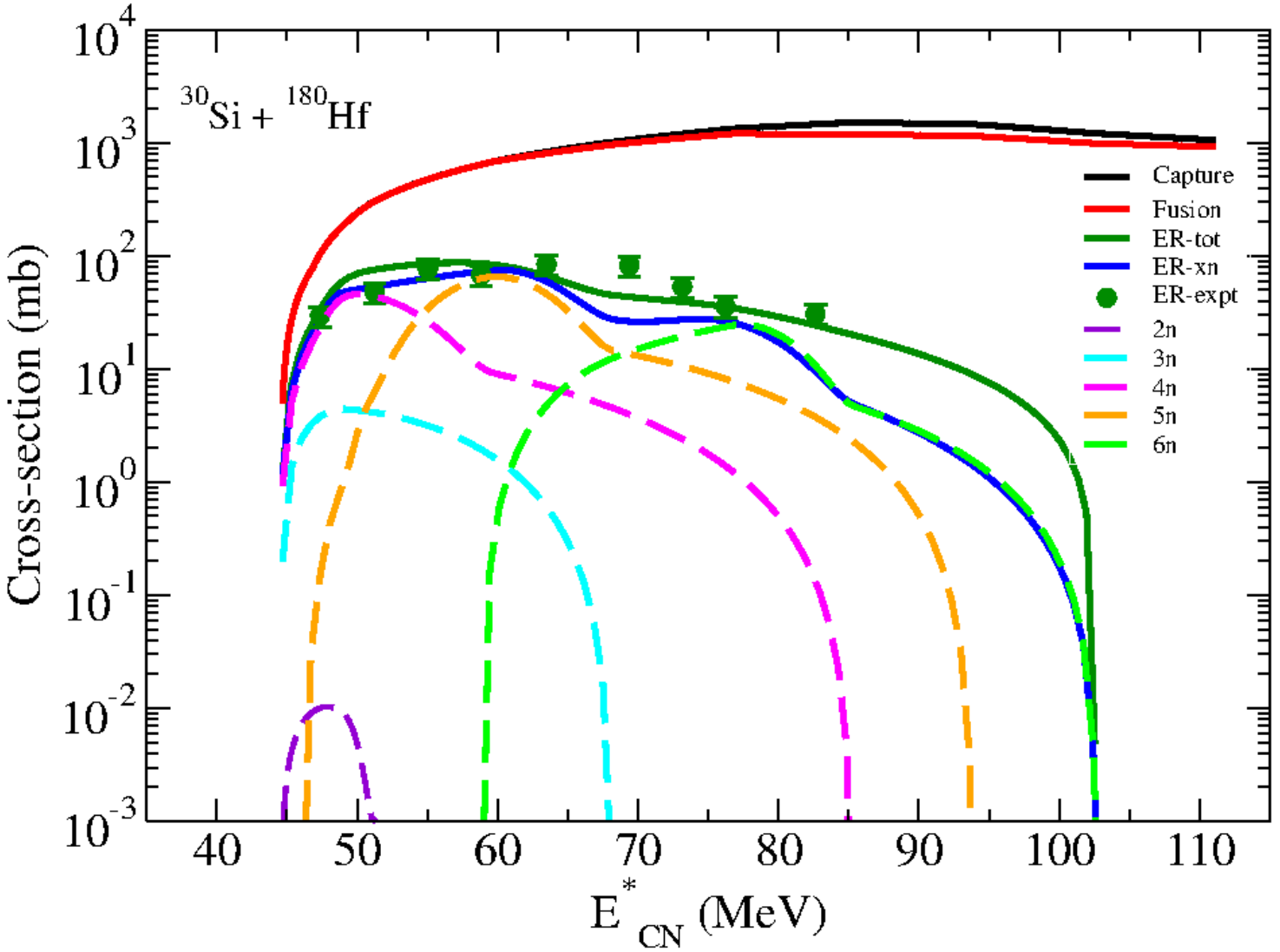
- Studied FF mass-angle and mass distributions for $^{30}Si+^{180}Hf$ system & compared with $^{16}O+^{194}Pt$ system, both populating same CN at similar excitation energies.
- ER cross sections are also measured.
- Different theoretical model calculations are also performed.
- Presence of Quasifission in more symmetric systems.
- Entrance channel dependence of QF is confirmed.

Collaborators

Central University of Kerala	• **Dr. E. Prasad**, Supervisor(Australian National University) • P. V. Laveen, M. Shareef
Inter University Accelerator Centre	• N. Madhavan, S. Nath, J. Gehlot, A. Jhingan • T. Varughese, Tathagata Banerjee
University of Mumbai	• S. Kailas
University of Calicut	• A. M. Vinodkumar
Joint Institute for Nuclear Research	• A. K. Nasirov
University of Messina	• G. Giardina, G. Mandaglio

Thank you


$^{16}O + ^{194}Pt$
Capture
Fusion
ER-tot
ER-xn
ER-expt
2n
3n
4n
5n
6n
Cross-section (mb)
E^*_{CN} (MeV)
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
40
50
60
70
80
90
100


^{30}Si + ^{180}Hf
Capture
Fusion
ER-tot
ER-xn
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2n
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4n
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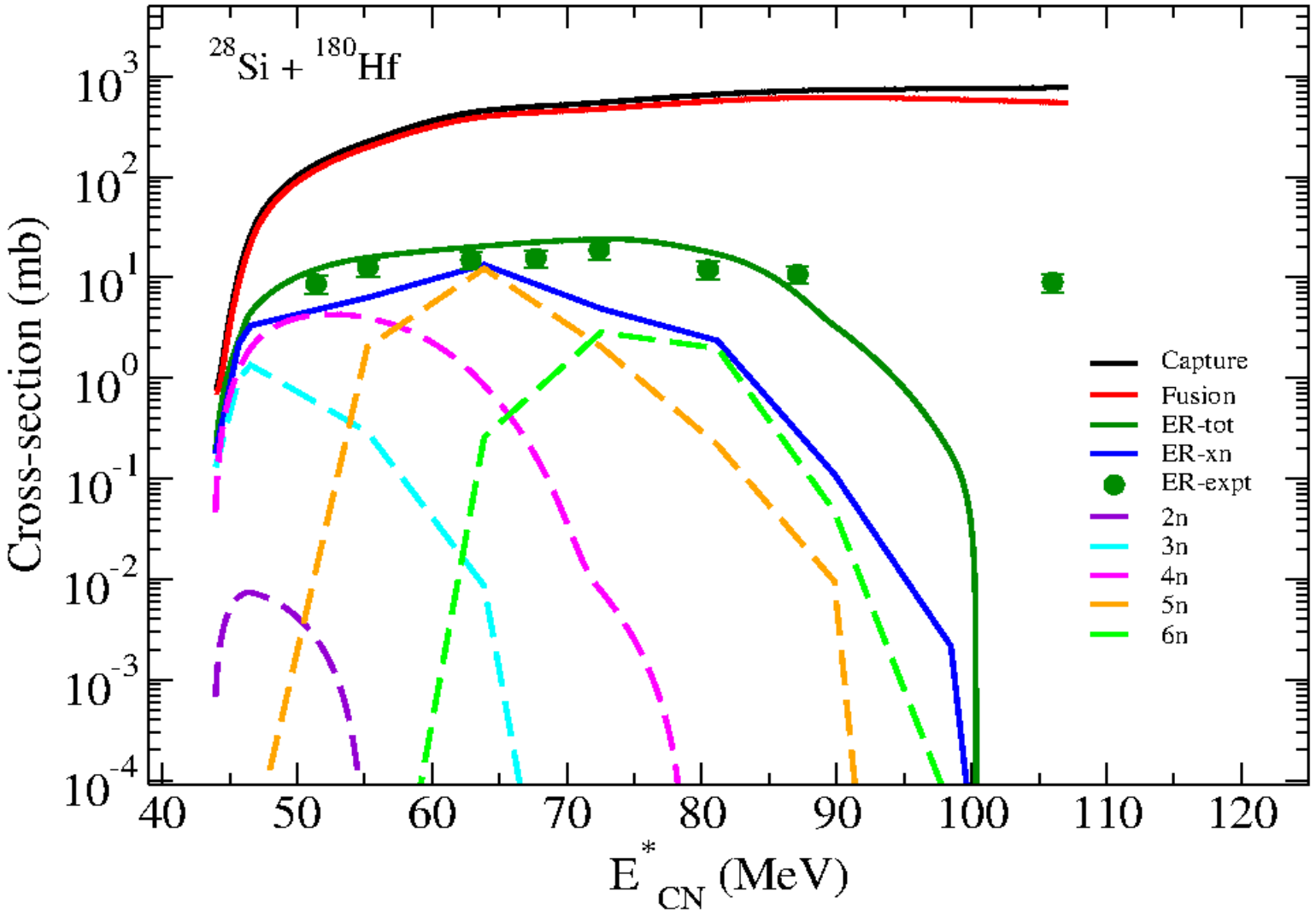
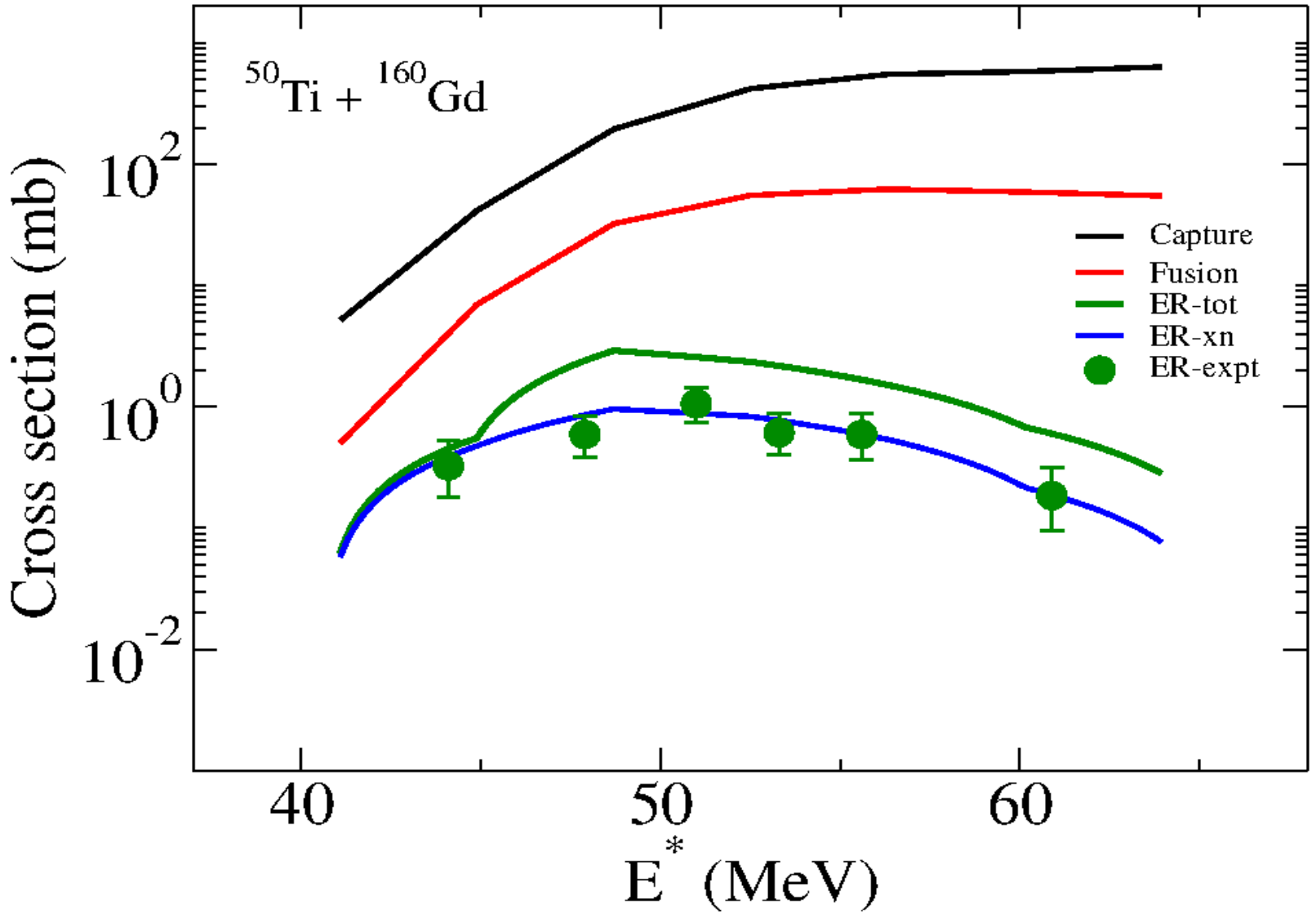
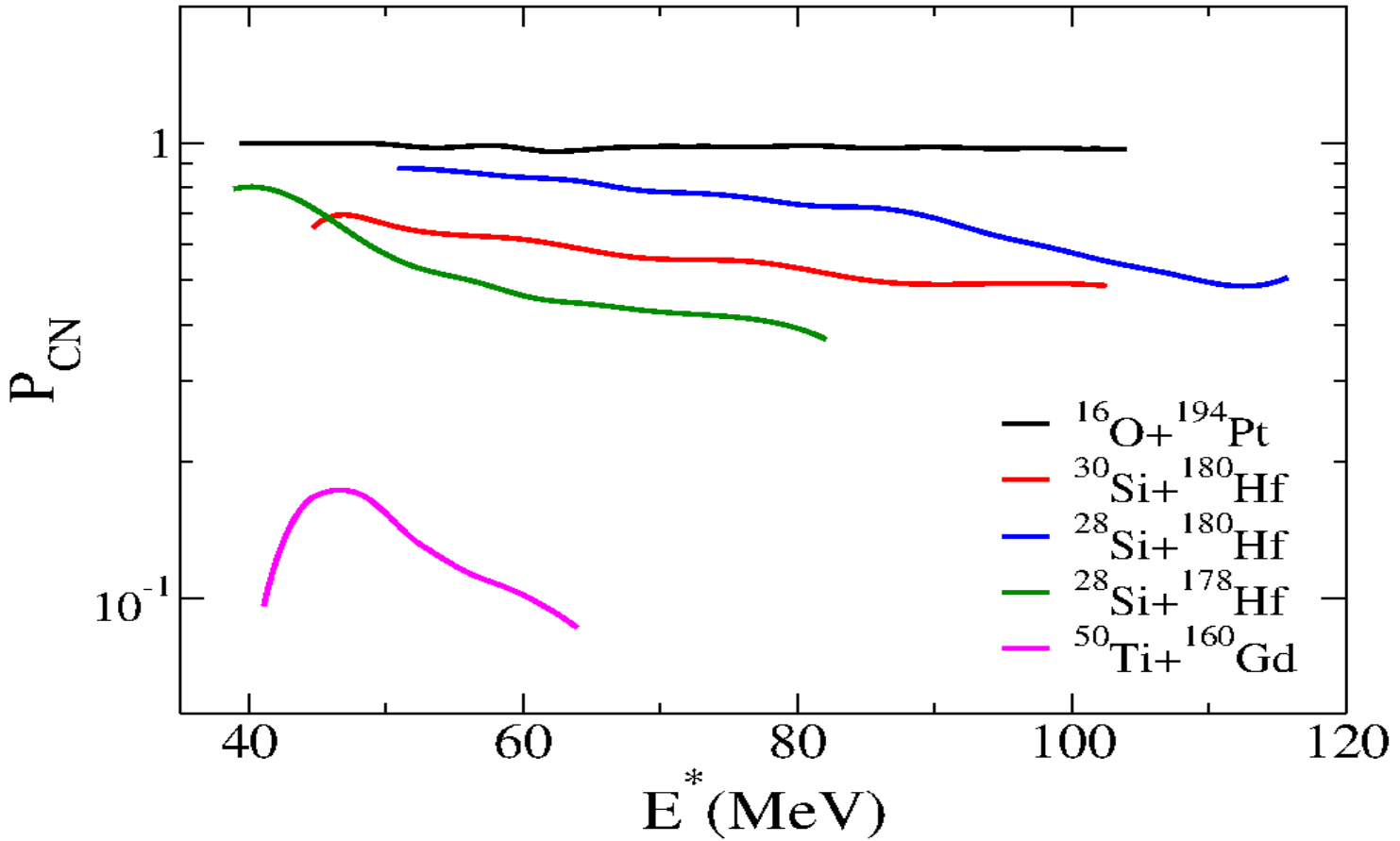
Cross-section (mb)
E^*_{CN} (MeV)
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
40
50
60
70
80
90
100
110


^{28}Si + ^{180}Hf
Cross-section (mb)
E^*_{CN} (MeV)
Capture
Fusion
ER-tot
ER-xn
ER-expt
2n
3n
4n
5n
6n

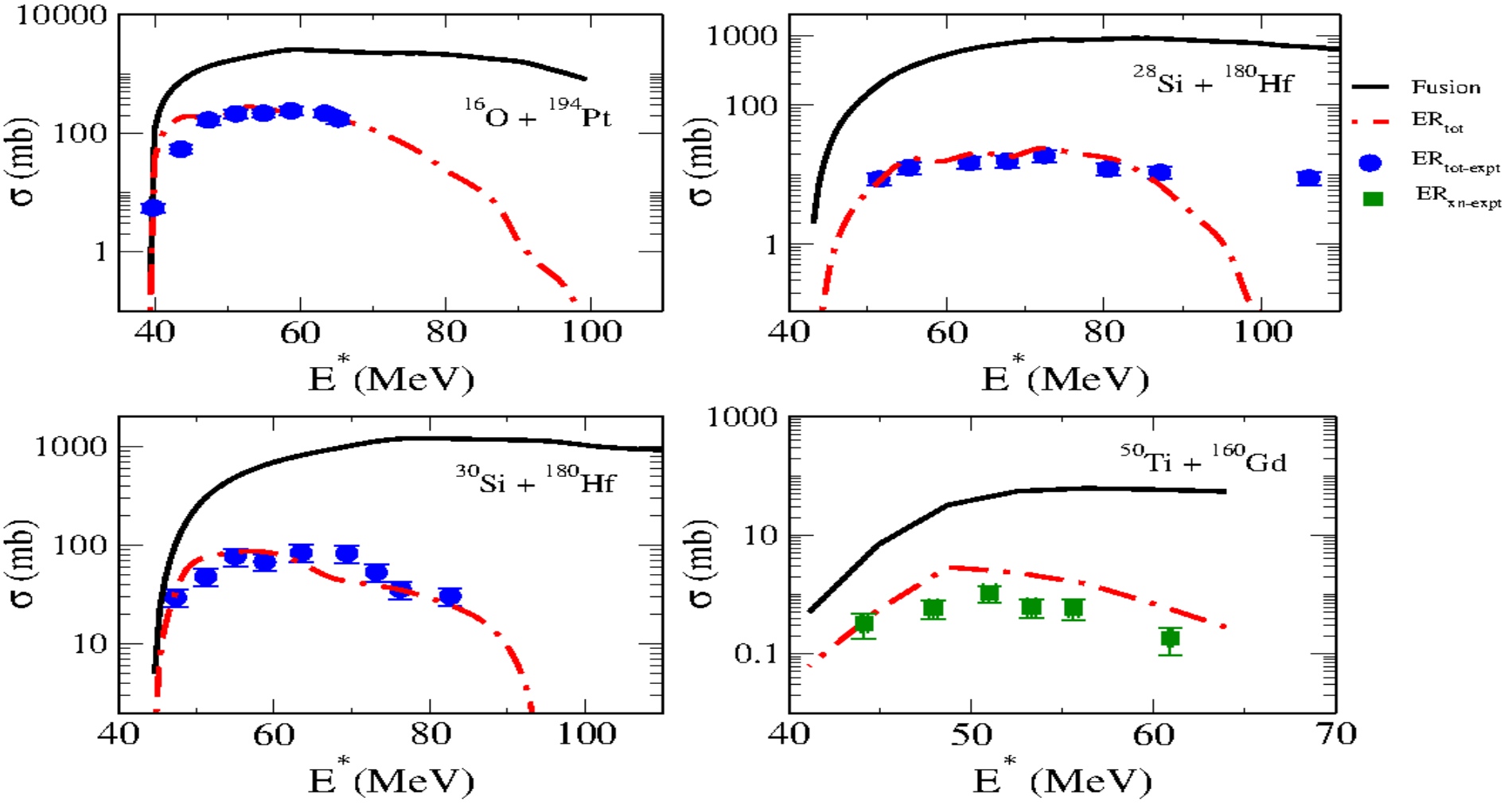

^{50}Ti + ^{160}Gd
Capture
Fusion
ER-tot
ER-xn
ER-expt
Cross section (mb)
10^{2}
10^{0}
10^{-2}
40
50
60
E* (MeV)

Fusion probability, P_{CN}

- The probability that the projectile-target system will form a completely fused system rather than reseparating (quasifission)

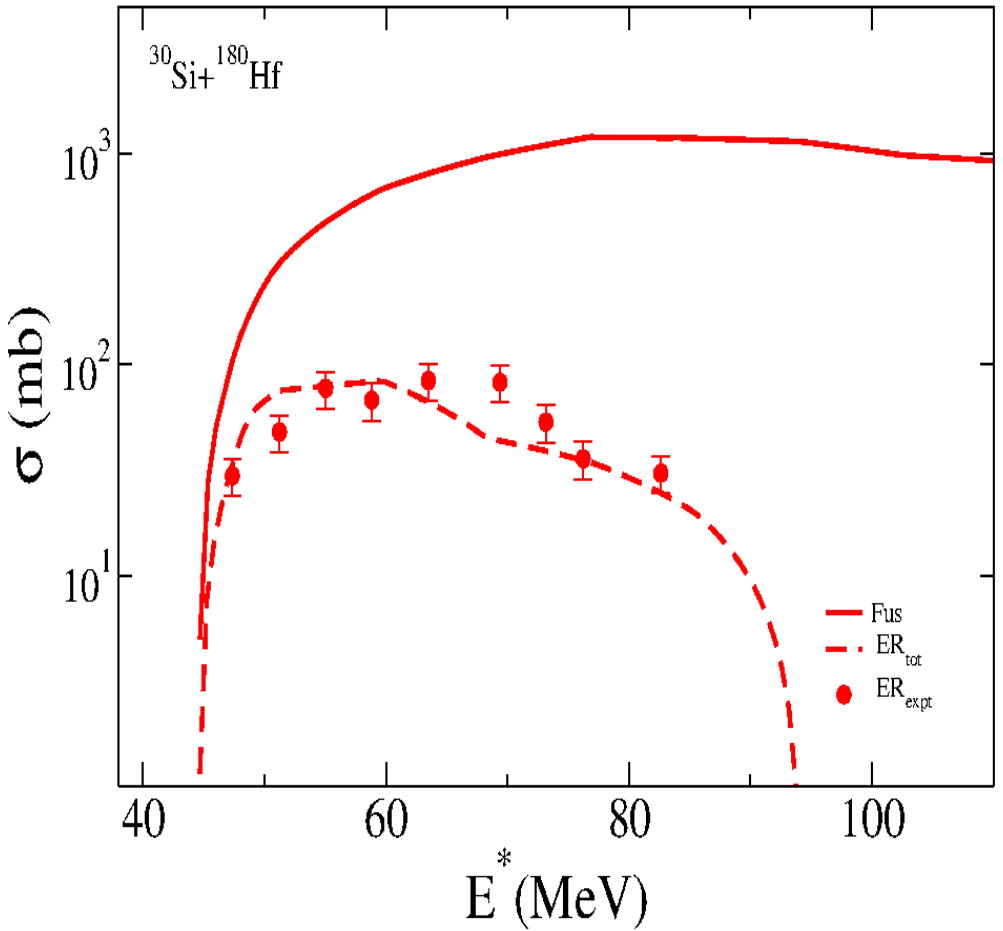


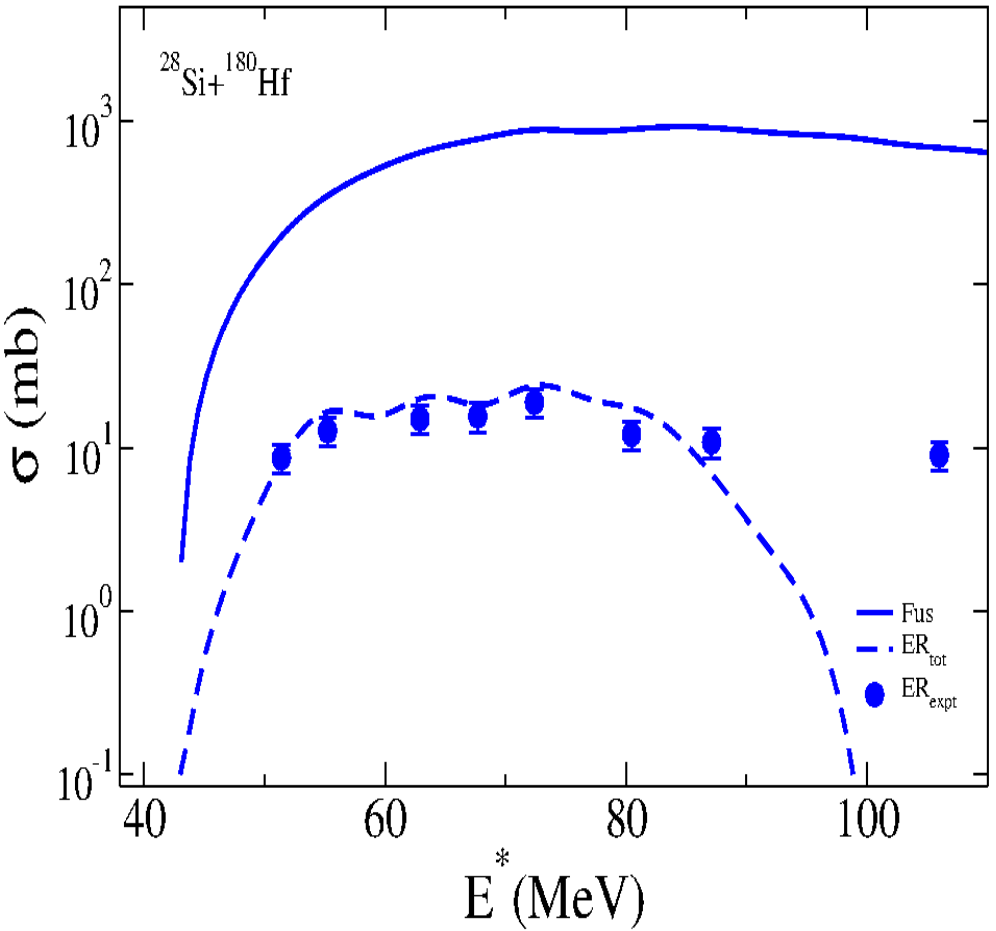
DNS Results



Butt et al., Phy Rev. C 66, 044601 (2002), D. A. Mayorov et al., Phys. Rev. C 92, 054601 (2015).

DNS Results


^{30}Si+^{180}Hf
σ (mb)
10^3
10^2
10^1
40
60
80
100
E* (MeV)
Fus
ER$_{tot}$
ER$_{expt}$


^{28}Si+^{180}Hf
σ (mb)
10^3
10^2
10^1
10^0
10^{-1}
40
60
80
100
E* (MeV)
Fus
ER$_{tot}$
ER$_{expt}$