Influence of exotic structure and weak binding on reaction dynamics near the Coulomb barrier

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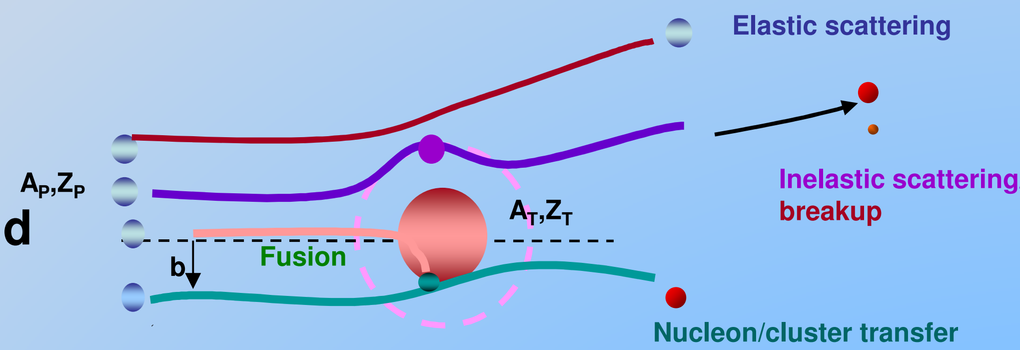
Current Status



Tightly bound nuclei:
$E \sim V_B$ - Rich interplay between reactions coupling to inelastic and transfer reactions

Weakly bound stable($^{6,7}Li$, ^{9}Be):
low lying continuum – importance of coupling to breakup
- **suppression in complete fusion at $E>V_b$**
- **Elastic scattering $-V_R$ repulsive , Breakup threshold anomaly**
- **Large intrinsic alpha cross-section, incomplete fusion x-section**

L.F. Canto et al, Phys. Rep. 424 (2006) 1

Weakly bound radio active nuclei:
- **exotic shapes, extended density distribution**
- **large probability of transfer of valence nucleon,**
- **isospin asymmetry**

N. Keeley, et al Prog. Part. and Nucl. Phys. 63, 396 (2009).

Recent Interest and challenges

Weakly bound stable nuclei

- **Deep sub-barrier: phenomenon of fusion hindrance? Fusion vs t/d capture?**
- **Importance of projectile break up vs. transfer followed by breakup?**
- **Understanding of breakup fusion mechanism?**

Radio active Ion Beam

- **Nucleon correlations influencing reaction dynamics**
- **Neutron rich vs neutron deficient nuclei**
- **Importance of large +ve Q value transfer important relative to Breakup**

Theoretical:

CDCC- predict breakup and total fusion x-section

Classical dynamical model: Complete, incomplete fusion, New feature-Time propagation of final products

Need: Comprehensive coupled channels taking into account transfer, breakup, Transfer breakup, complete and incomplete fusion…

Lay out of the talk

Weakly bound stable nuclei: Mumbai Pelletron

Exploring fusion hindrance at deep sub-barrier energies

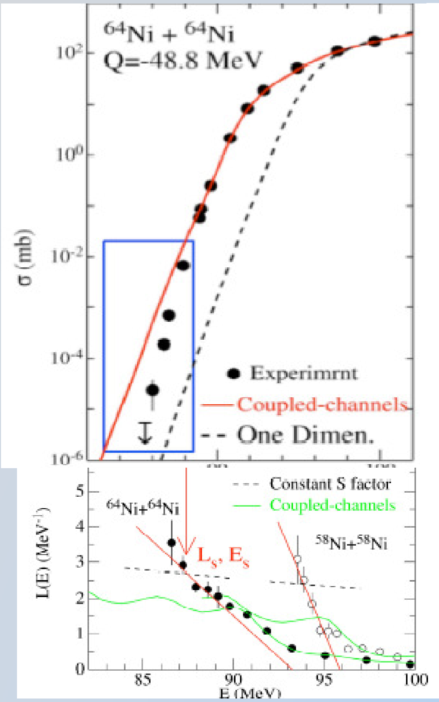
^{6}Li + ^{198}Pt, ^{7}Li + ^{198}Pt,
^{12}C + ^{198}Pt

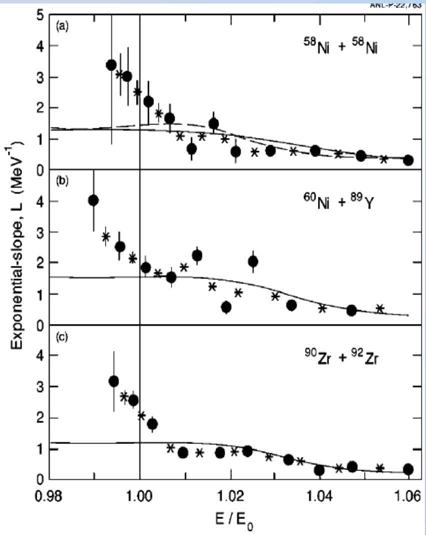
Weakly bound exotic nuclei: SPIRAL , GANIL

Tunneling of most neutron rich nuclei

^{8}He + ^{197}Au, ^{65}Cu

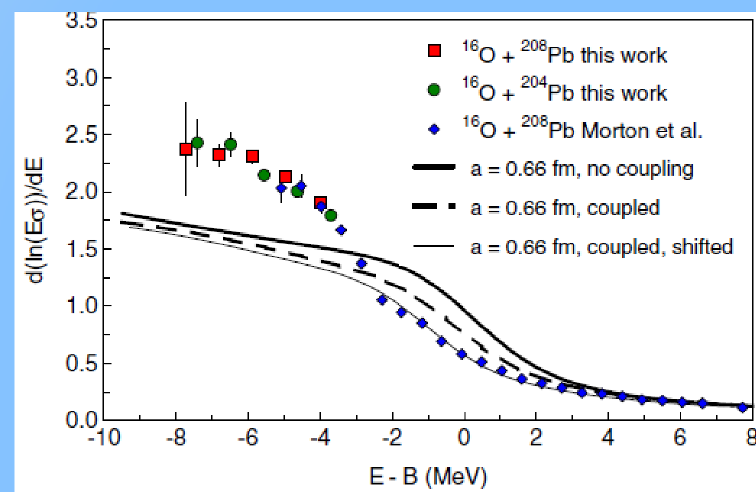
Hindrance in deep sub-barrier fusion cross-section





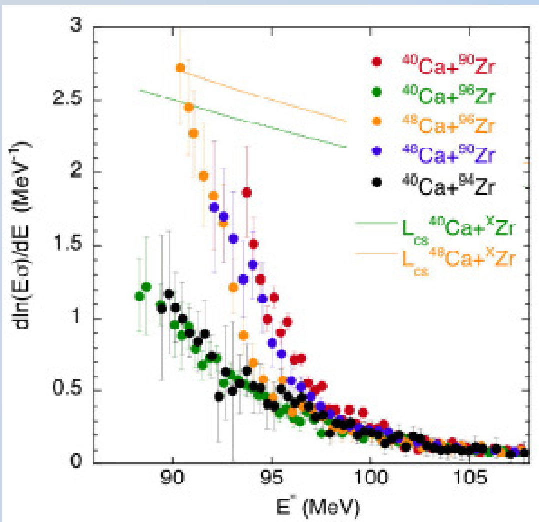
Challenging low x-section data from ANL: Jiang et al. PRL 89 (2002) 052701
Mostly medium-heavy mass symmetric systems (different Q value, stiffness reduced mass values, neutron excess)
Steep fall off σ_{fus}(E) , sharp rise in L(E)

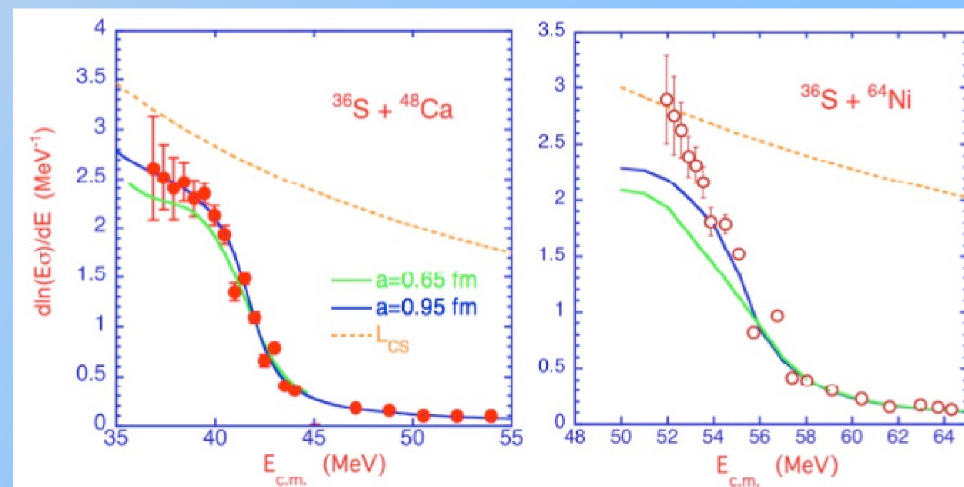
Asymmetric ^{16}O+^{208}Pb:
Dasgupta et al
PRL99(2007)192701
Saturation of L(E)



Recent measurements

Medium – light system : unsystematic behavior
Stefaninni, et al PRC 82,014614(2010), Fusion08 proceedings,
Jiang et al PRC 82,041601 (R)2010





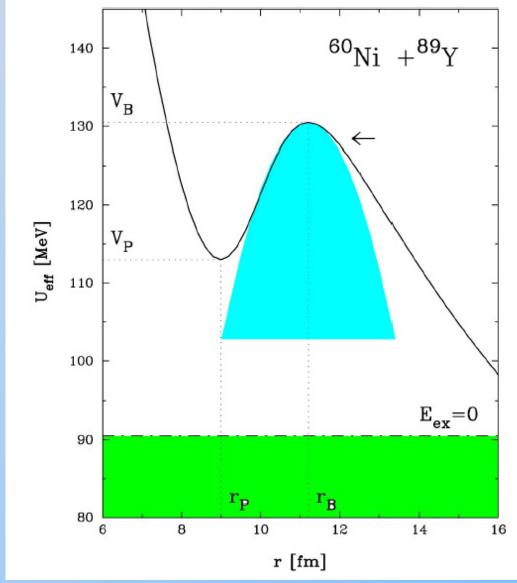
light nuclei– ANL astrophysical reaction rates eg $^{13}C+^{12}C$ NPA834(2010)192c

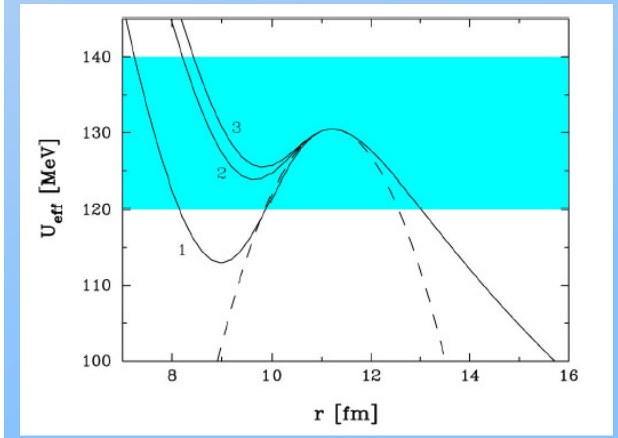
More measurements with different entrance channel required to understand behavior at E<<Vb, when influence of coupling vanishes

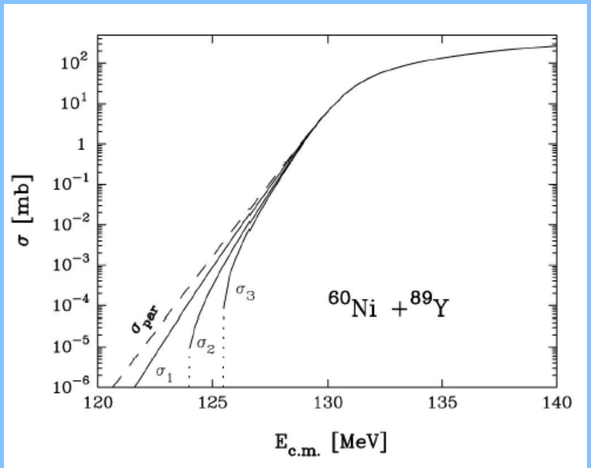
Present understanding

Deep sub-barrier fusion – probe to study inner part of inter-nuclear potential

- Dasso & Pollarolo et al PRC68,054604







Models

Fusion hindrance observed at deep sub-barrier in stable- symmetric system explained

Sudden model: Potential with shallow pocket: M3Y double folding+repulsive core (Pauli Blocking) reproduces nuclear incompressibility - Esbensen & Misicu

Adiabatic model: two step via neck formation – Ichikawa & Hagino

Fusion with weakly bound nuclei at deep sub-barrier energies

To study phenomenon of fusion hindrance

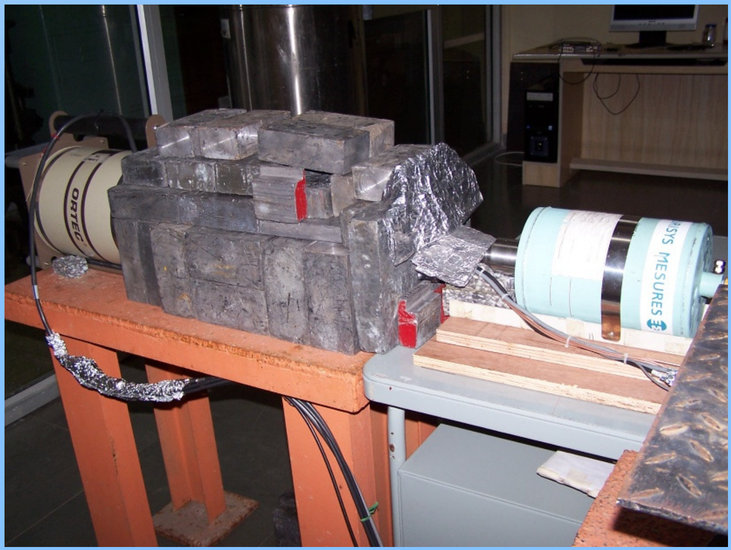
^{6}Li beam from Mumbai Pelletron on ^{198}Pt
(~ 1 mg/cm2 thick 95.7 % enriched)

First measurement with weakly bound projectile at $0.68 < E/Vb < 1.3$

Q=+8.5 MeV

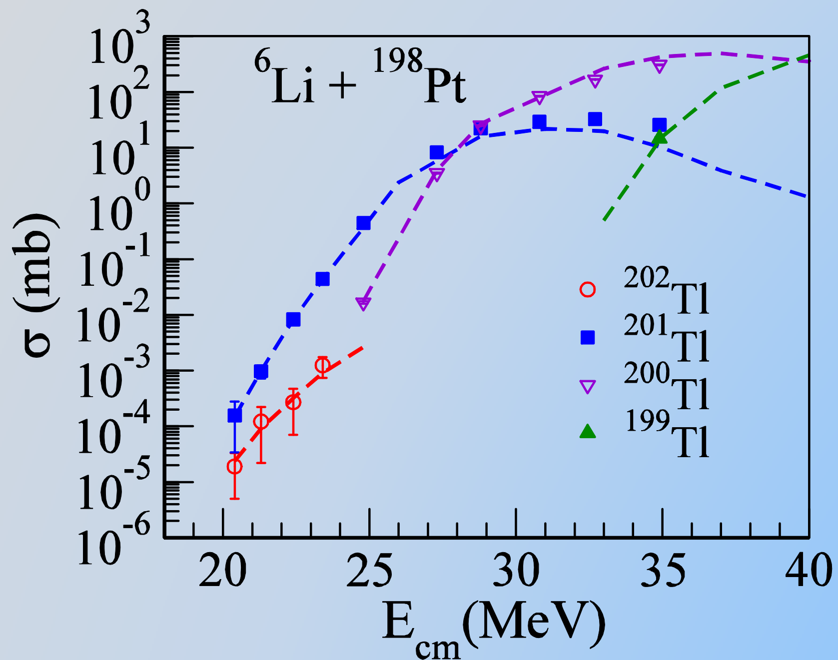
New sensitive off-beam gamma spectroscopy Technique:

coincidence between characteristic KX rays and gamma rays of daughter nuclei
Lemasson et al NIM 598, 445 (2009)



2 HPGe inside low background setup

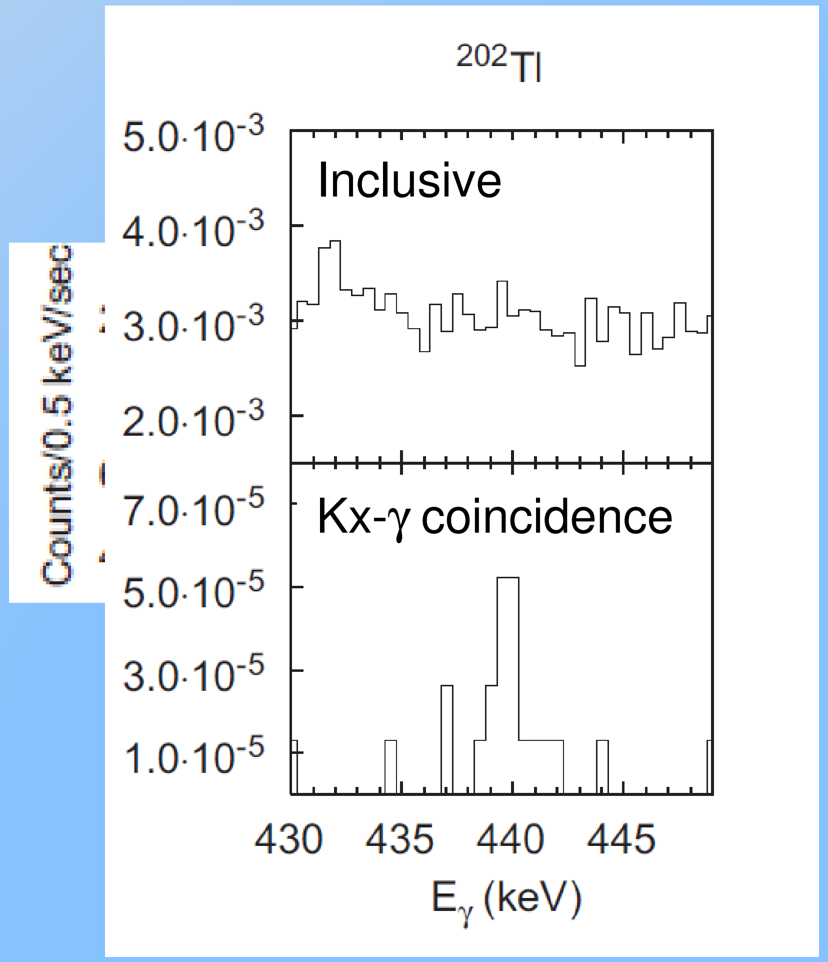
Evaporation residue cross-sections



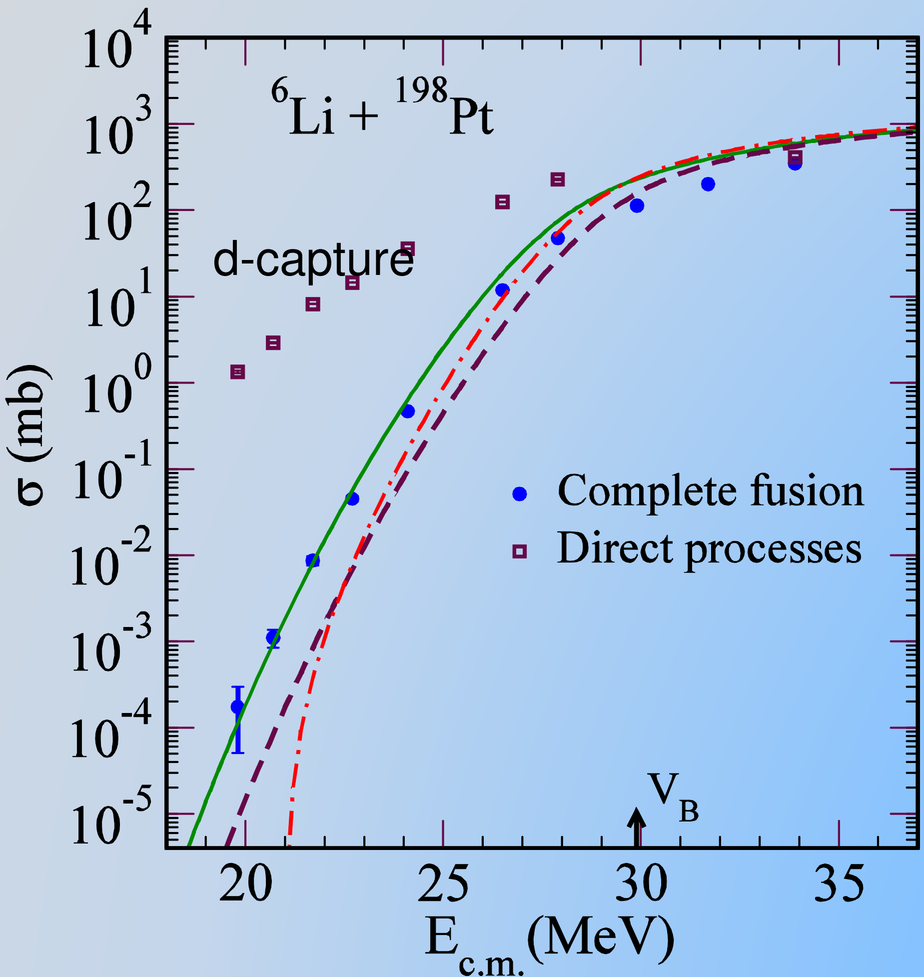
Lowest x-sec up to 20 nb

Statistical model calculations (PACE) with shell corrected level densities.

Reduction of background



Fusion cross-sections



Couple channel calculations
CCFUL (WS potential)
Calculations – by K. Hagino

Solid curve: with coupling to ^{198}Pt and ^{6}Li inelastic states

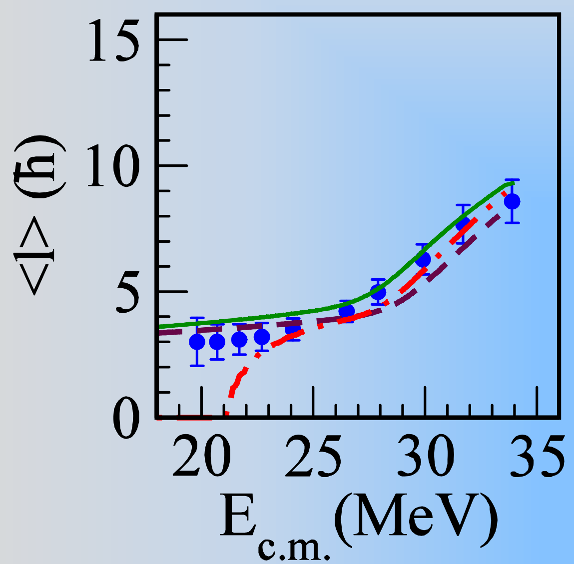
Dashed curve: no coupling

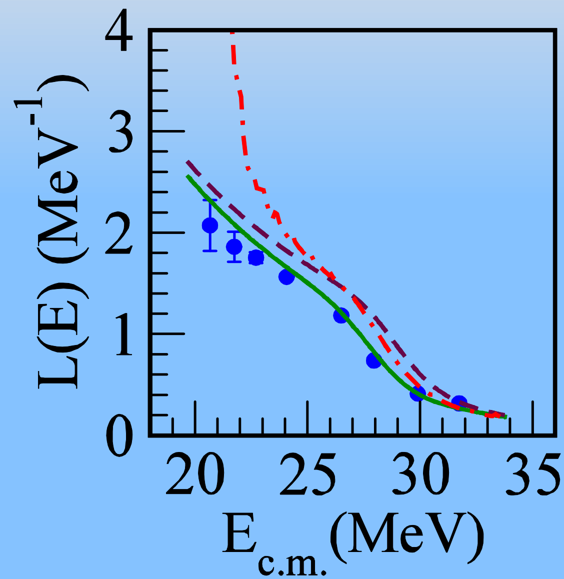
Single channels calculations
M3Y+rep core – dashed dot line

No fusion hindrance observed

A. Shrivastava et al Phys. Rev. Letts 103(2009) 232702

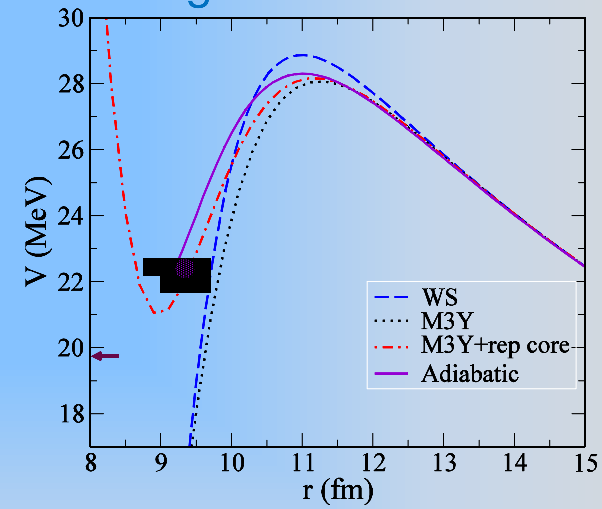
Average angular momentum, logarithmic derivative





CC calculations with WS potential (solid curve) explain <l> and L(E)
Absence of hindrance

Hagino and Ichikawa

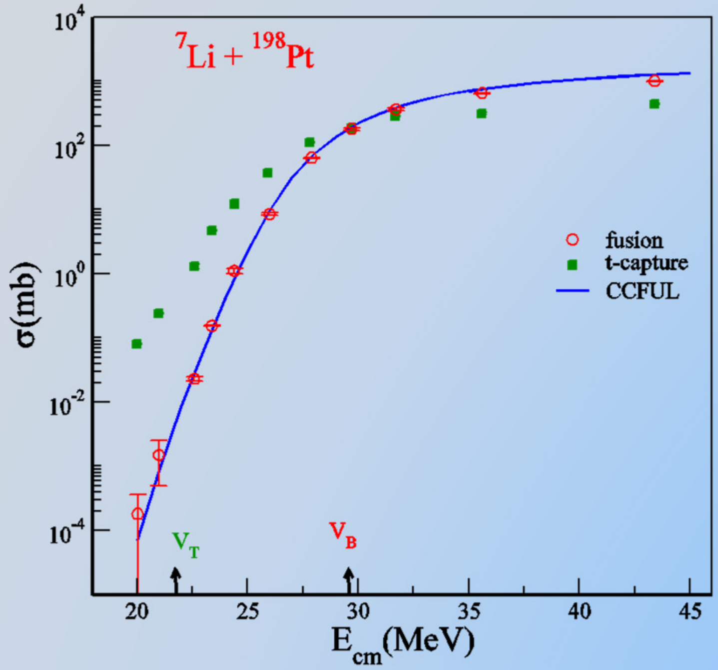


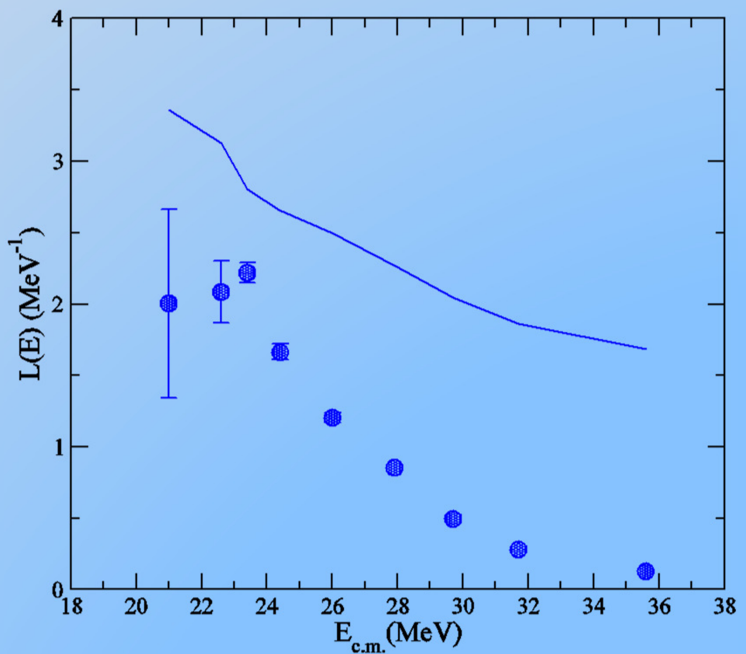
Modification required both in Sudden & Adiabatic models to take in to account weakly bound and asymmetric system

below the threshold energy for observing fusion hindrance

Internucleus potential deeper, less shallow, less repulsive core…adiabaticity?

Weakly bound asymmetric system: $^{7}Li+^{198}Pt$





10 MeV below V_B, Couple channel calculations explain data

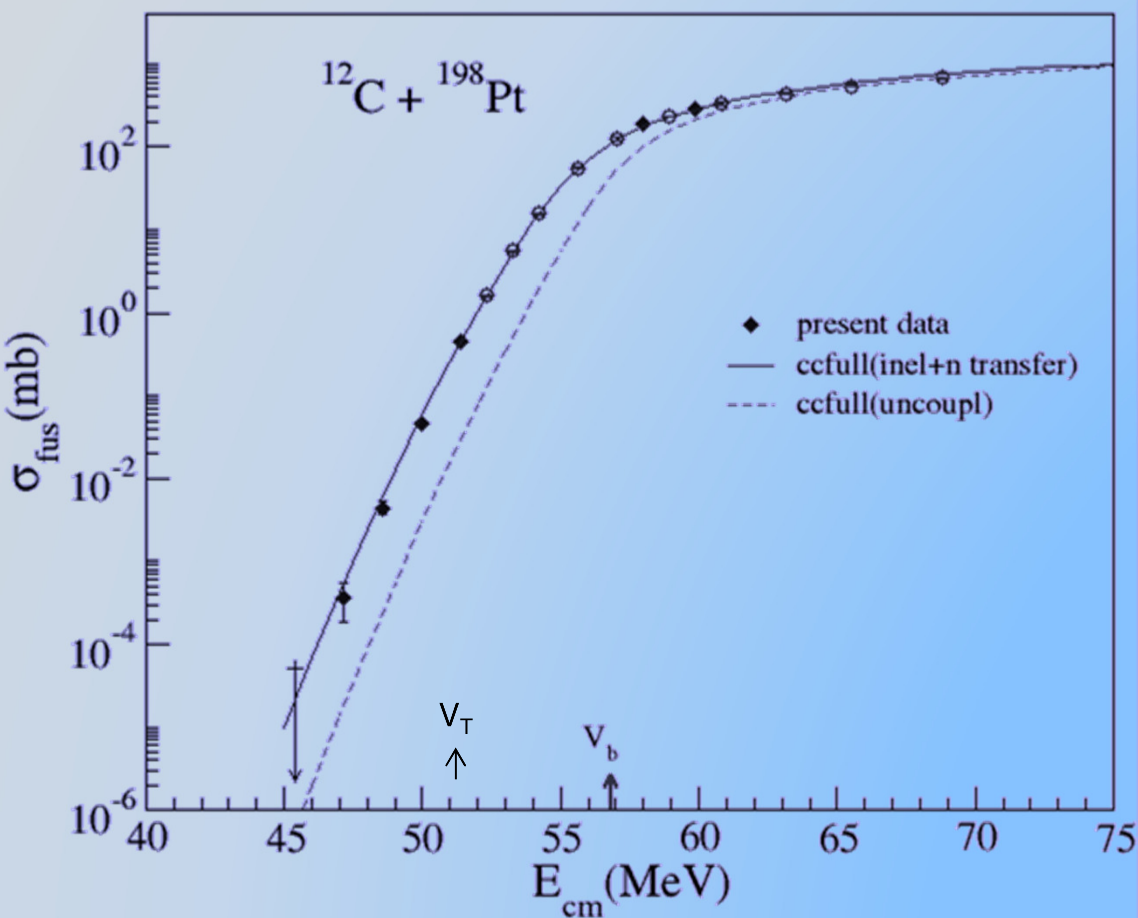
t-capture most dominant

No sharp change in slope

Fusion hindrance not observed

Asymmetric system with stable projectile

$^{12}C+^{198}Pt$ at deep sub barrier energies

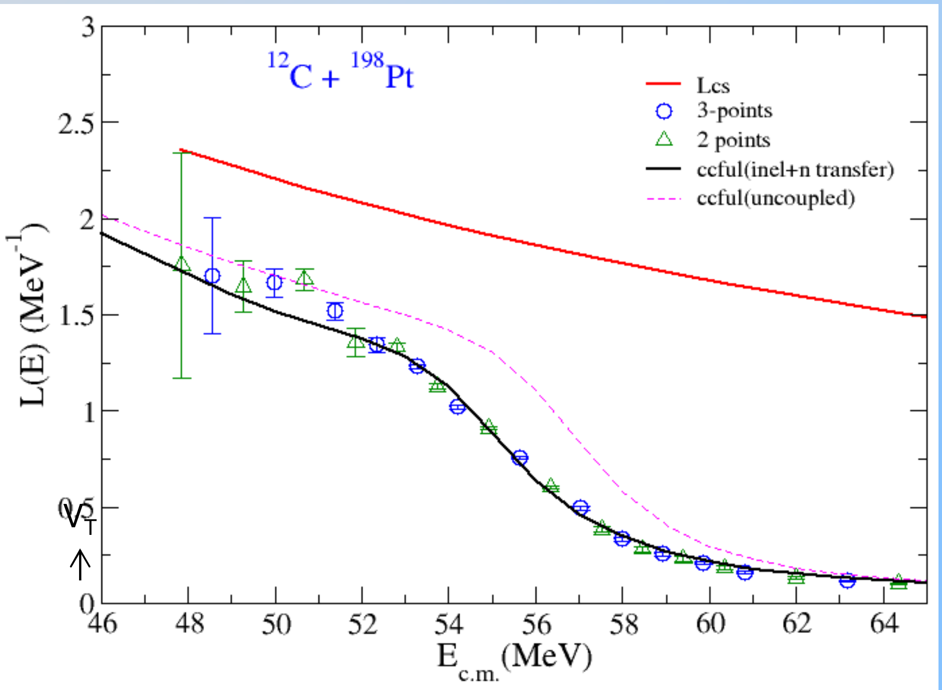


Data from
A.Shrivastava et al PRC 63, 054602 (2001)
Extended to lower energies

CCFULL calculations :
Inelastic states of target and projectile in vibrational mode and 1n,2n transfer
(2n Q value= - 0.3 MeV)

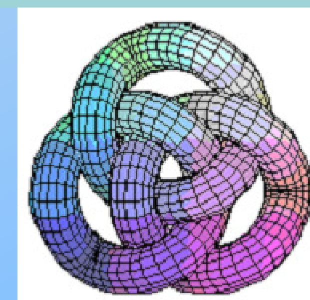
No change in slope with respect to calculations

Logarithmic derivative and barrier distribution



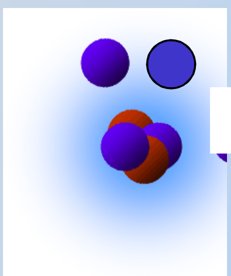
At deep sub barrier energies
No pronounced fusion hindrance for asymmetric systems
with weakly bound and stable projectile: ^{6}Li, ^{12}C, $^{7}Li + ^{198}Pt$

Reactions with exotic He nuclei

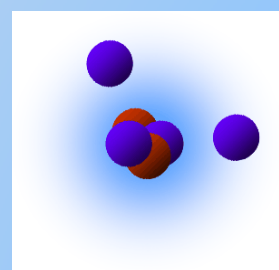


Addition to Weak binding – large isospin
Exotic structure – Halos and skin

Borromean Nuclei ^{6}He



$2n+^{4}He$
Di-neutron



$n+^{4}He + n$
cigar

t + t

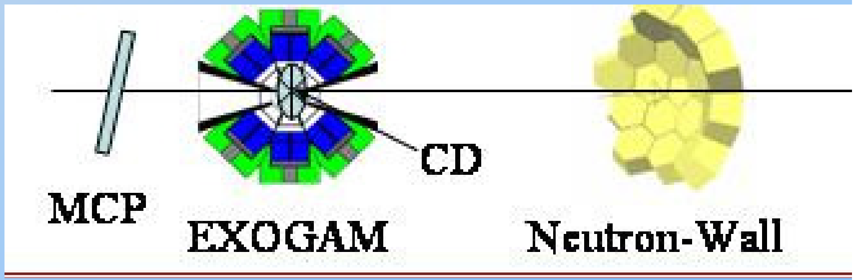
Dominance of di-neutron configuration: $^{6}He+^{65}Cu$, $\sigma(2n)/\sigma(1n)$

Transfer measurement ^{6}He + ^{65}Cu

SPIRAL GANIL

E_L=23 MeV

High Current 4.5x10^{7} /sec ^{6}He
Detector Arrays



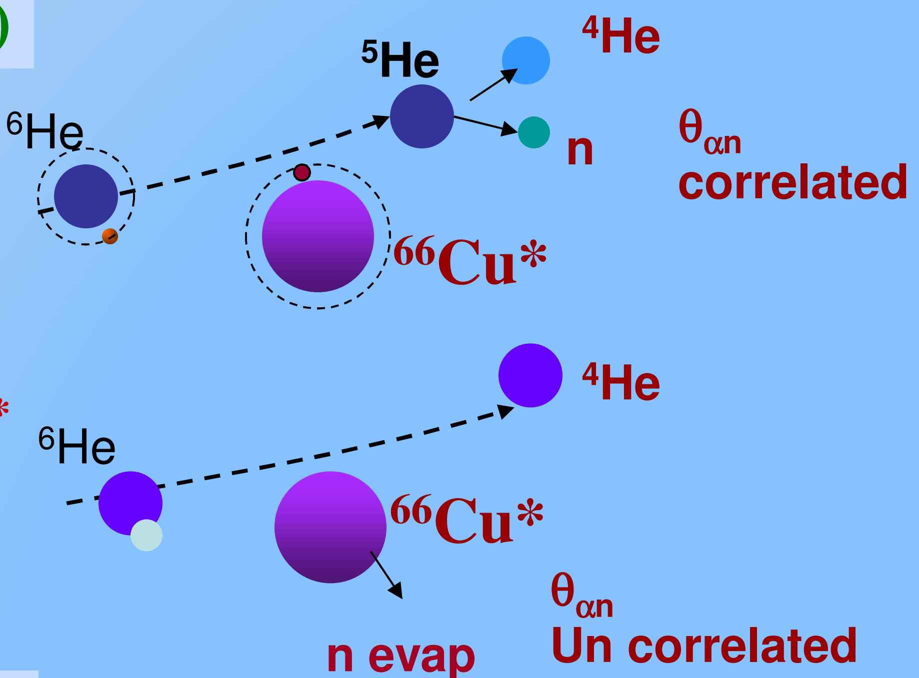
Triple coincidence with RIB (p-n-γ)

1n and 2n transfer

^{6}He+^{65}Cu → (1n) ^{5}He+ ^{66}Cu*

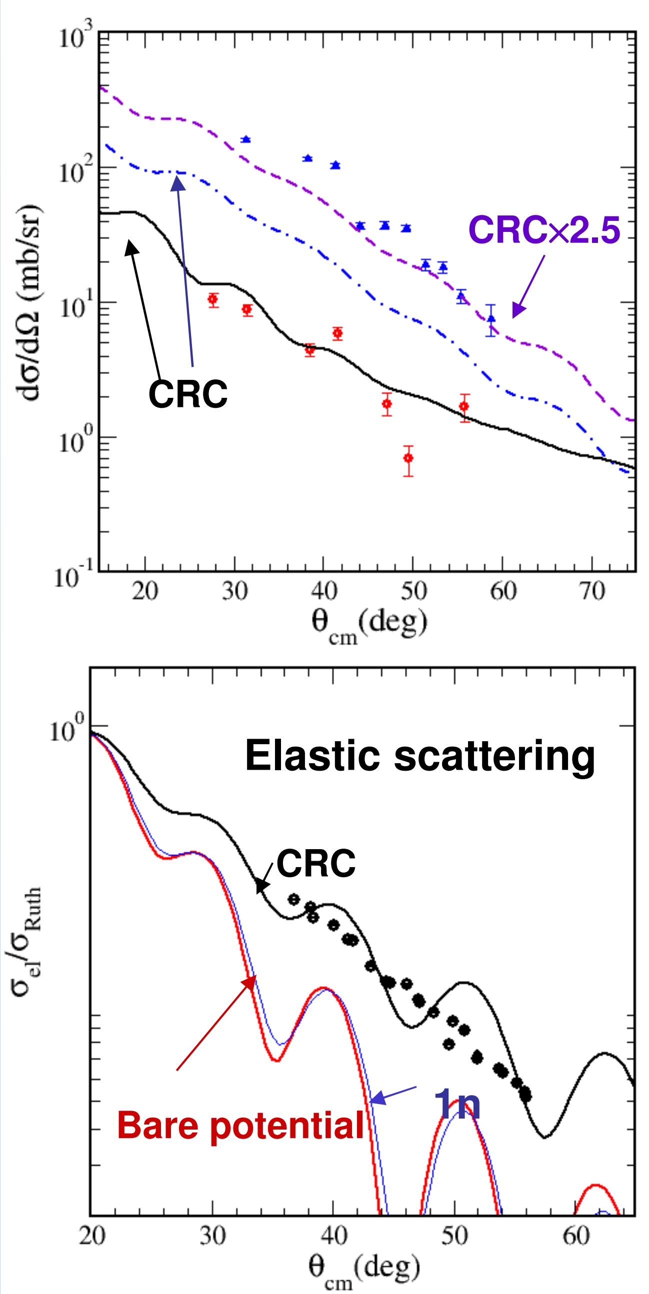
^{6}He+^{65}Cu → (2n) ^{4}He+(^{67}Cu)*

^{4}He + γ(^{66}Cu) + n



Energy Angular correlations
To separate 1n /2n transfer

Angular distribution

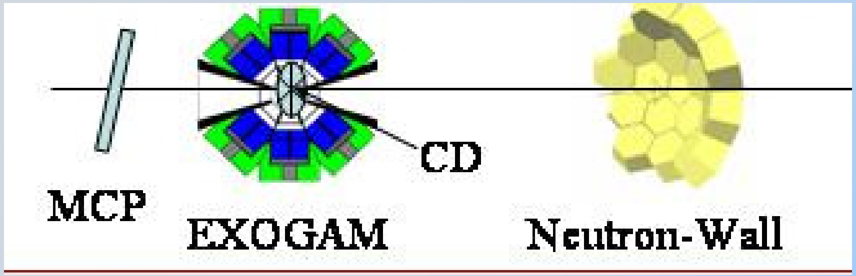


2n transfer > 1n transfer
naively – di neutron dominant

CRC calculations
Transfer
2n transfer - assumed pair transfer
Elastic :
strong effect of transfer coupling
Fusion
expt = 1375 ±220
CRC cal = 1655, 1614 and 1533 mb
(bare, 1n and 1n+2n calculations)

A. Chatterjee et al. PRL , 101 (2008)032701

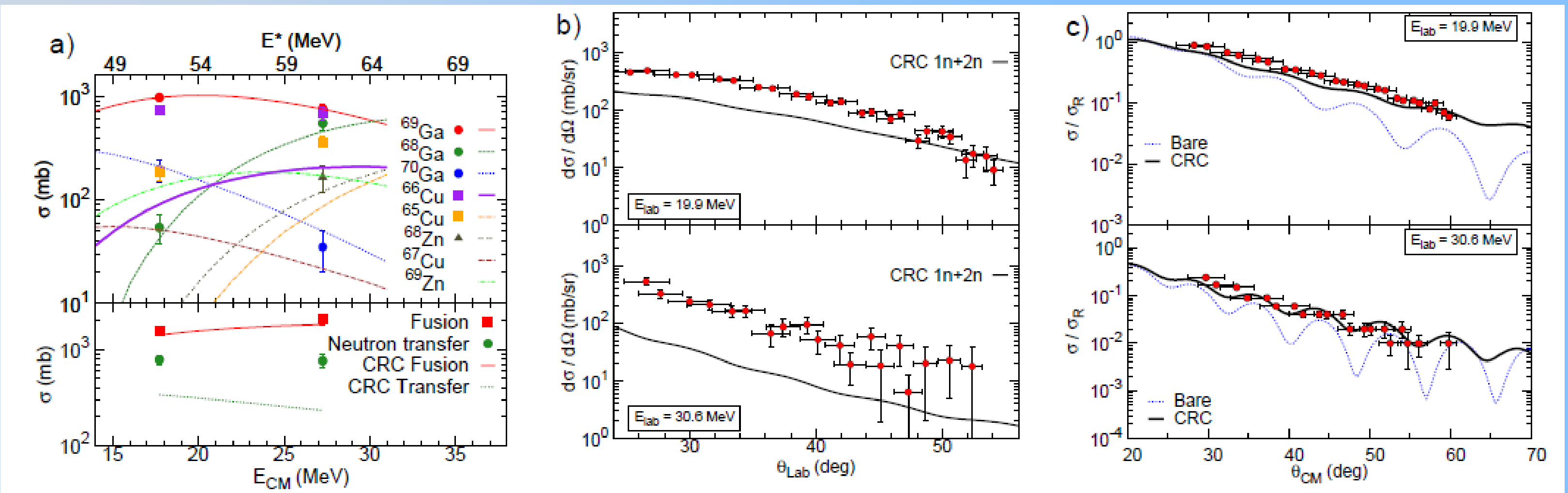
Complete reaction studies $^{8}He+^{65}Cu$



E= 19.9, 30 MeV

Elastic scattering ang dist: ^{8}He
Transfer ang dist: $^{4,6}He+\gamma$ ($^{65,66}Cu$)
Fusion: inclusive gamma ERs

Fusion, Transfer (1n+2n) Elastic scattering



PRC 044,617(2010); PLB 697, 454 (2011)

Tunneling of the most neutron-rich nucleus

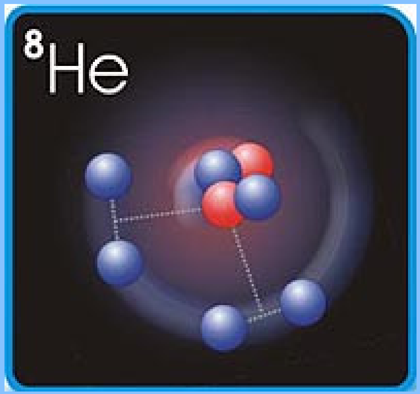
He isotopic chain:

- **Nucleon emission threshold from 20.5 MeV to 0.9 MeV**
- **^{6}He and ^{8}He "Borromean" structures**
- **^{8}He : ^{4}He + 4n ^{6}He+2n (double Borromean)**
- **Charge radius of ^{6}He > ^{8}He,**
- **Neutron separation energy ^{6}He < ^{8}He**

^{8}He: largest N/Z ratio, strong di-neutron correlations
interesting case to study tunneling probability

^{4}He + 4n, ^{6}He+2n

Chulkov et al NPA759(2005)43



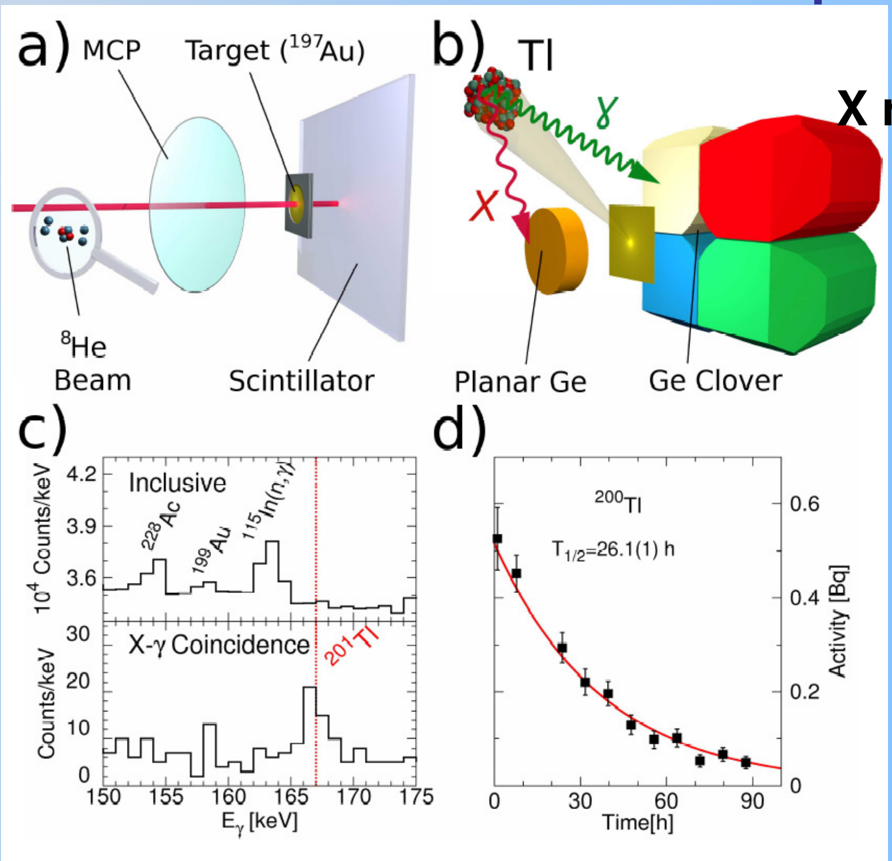
Experiment configuration

Primary beam: ^{13}C (75 MeV/A) on thick graphite,
Secondary beam: ^{8}He, fully purified and reaccelerated at CIME
Target : ^{197}Au (6mg/cm^2) (stack ^{197}Au +Al)

Detection: sensitive off beam technique

^{8}He ~4x10^{5}pps

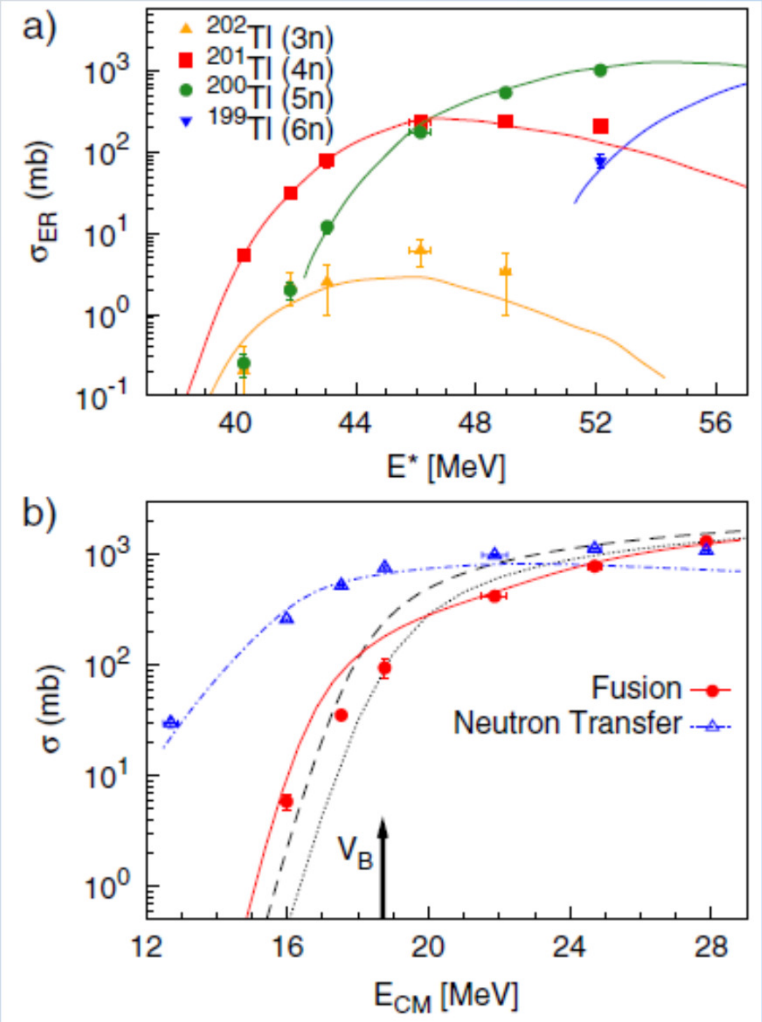
X ray-gamma ray coinc



sensitivity

selectivity

Fusion and Neutron Transfer



Evaporation residues from CN ^{205}Tl
First accurate low x-sec at sub-barrier with low intensity RIB

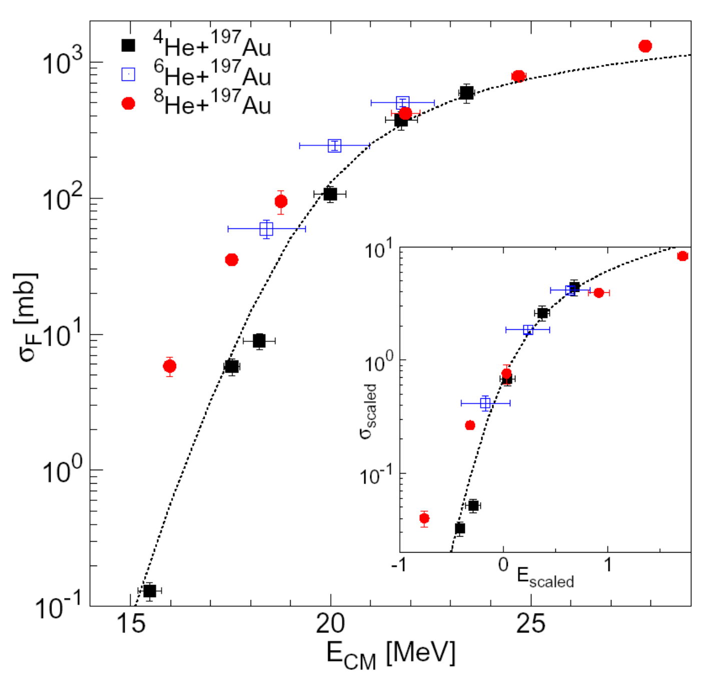
Good agreement with statistical model calculation

Transfer x-section larger than fusion

Couple channel calculations –1n,2n neutron transfer

A. Lemasson et al PRL 103, 232701 (2009)

Comparison of tunneling in He isotopes



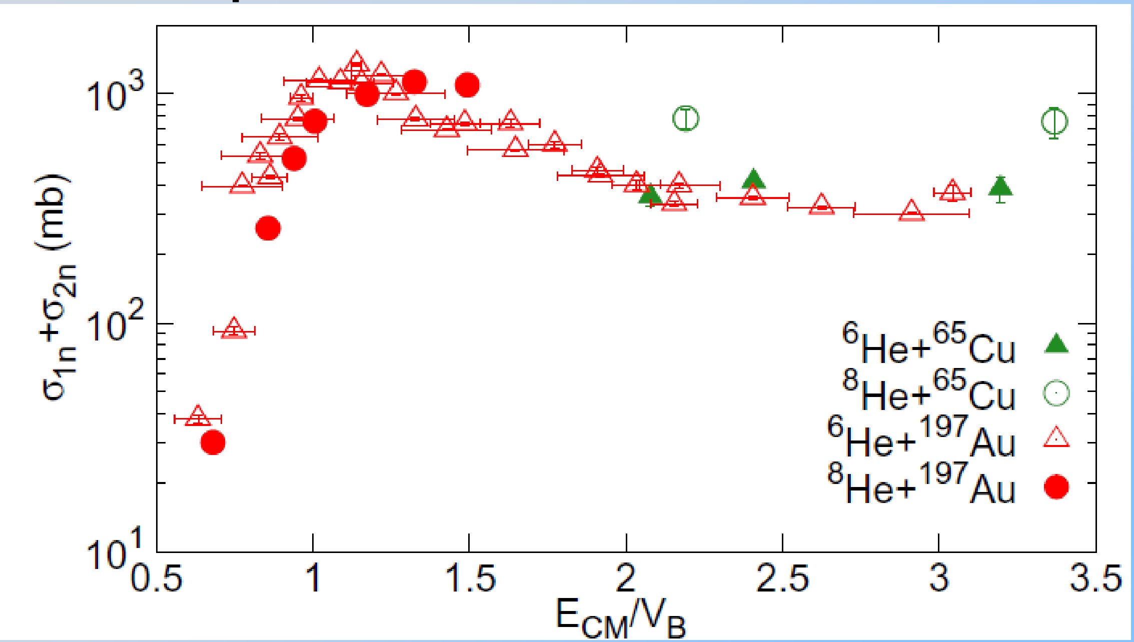
$\sigma_{fus}(^{6,8}He > \sigma_{fus}(^4He)$

$\sigma_{fus}\ (^6He) \sim \sigma_{fus}(^8He)$

^{8}He -easier to transfer excess neutron in peripheral reaction than to tunnel

A. Lemasson et al PRL 103, 232701 (2009)

Comparison of Neutron transfer $^{6,8}He$



x-sec ^{8}He> ^{6}He at higher energies, both targets
- **difference in geometry of valence neutrons in these isotopes, neutron correlations different in ^{8}He and ^{6}He**

Dynamics of such processes with loosely bound neutrons is a subject of deeper theoretical studies.

PRC 044,617(2010); PLB 697, 454 (2011)

Summary and outlook

- **No pronounced fusion hindrance for asymmetric systems with weakly bound and stable projectile: $^{6}Li, ^{12}C, ^{7}Li + ^{198}Pt$:**
  More measurements ^{9}Be, $^{6,7}Li + ^{197}Au, ^{198}Pt$, $^{11}B + ^{198}Pt, ^{197}Au$ etc. planned

- **Calculations based on Sudden and adiabatic model need modification for asymmetric projectile-target systems (weakly bound and stable)**

- **Tunneling probability of $^{8}He \sim {}^{6}He$**
  Neutron transfer probability $^{8}He > {}^{6}He$ E>Vb
  Neutron transfer dominant role deciding reaction dynamics
  dependence on geometry and correlations of valence neutrons

- **Advancement in theoretical models required**
- **Similar measurements on other neutron rich as well as proton rich nuclei**

Collaborator

$^{6,7}Li$, ^{12}C+^{198}Pt work

K. Ramachandran, K. Mahata, A. Chatterjee , S. Kailas , V.V. Parkar , P.C. Rout, C. Palshetkar, S. Pandit

BARC

A. Navin, A. Lemasson, M. Rejmund

GANIL

V. Nanal, R.G. Pillay, S. Thakur

TIFR

S. Bhattacharyya,

VECC

$^{8}He + {}^{197}Au, {}^{65}Cu$ work

A. Navin, A. Lemasson, M. Rejmund, S. Bhattacharya, C. Schmitt, A. Chatterjee, K. Ramachandran, J. Nyberg, V. Nanal, R.G. Pillay,, I. Stefan, D. Bazin, Y. Blumenfeld, D. Beaumel, G. de France, M. Labiche, A. Lemanson, R. Lemmon, R. Raabe, J.A. Scarpaci, C. Simenel, C.Timis,N. Keely, V. Zelevinsky

GANIL; BARC, TIFR, VECC, Upsalla; MSU, IPN Orsay, Univ. of Surrey, Daresbury Lab, Univ of Leuven, CEA Saclay, NSCL MSU

THANK YOU