Exploring the coupling to nucleon transfer in fusion involving nuetron-rich Sn nuclei at energies near the Coulomb barrier

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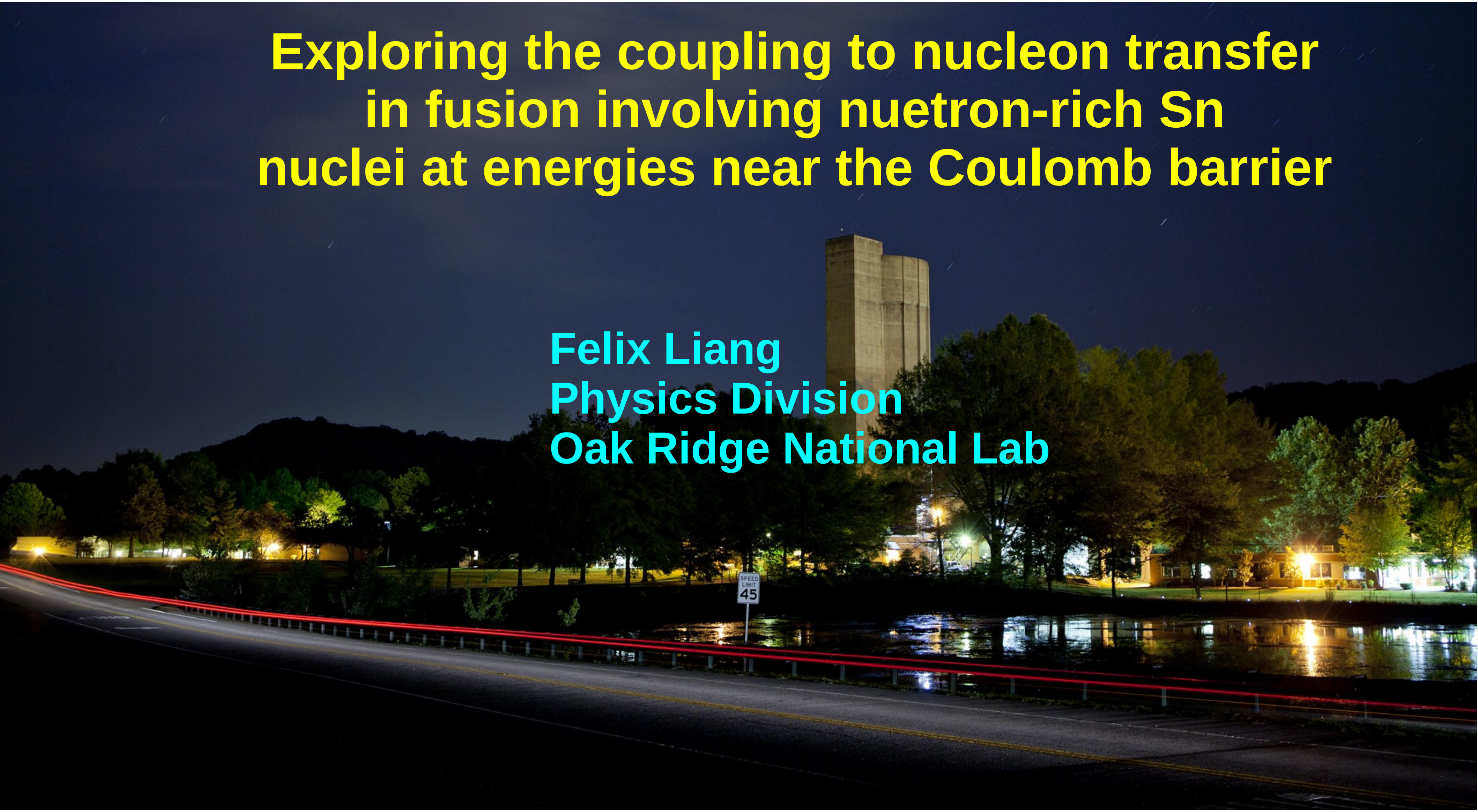


Outline

Introduction

fusion with neutron-rich radioactive nuclei

Experiment

Fusion enhancement and nucleon transfer

$^{132}Sn+^{40,48}Ca$

$^{132}Sn+^{58,64}Ni$

$^{46,50}Ti+^{124}Sn$

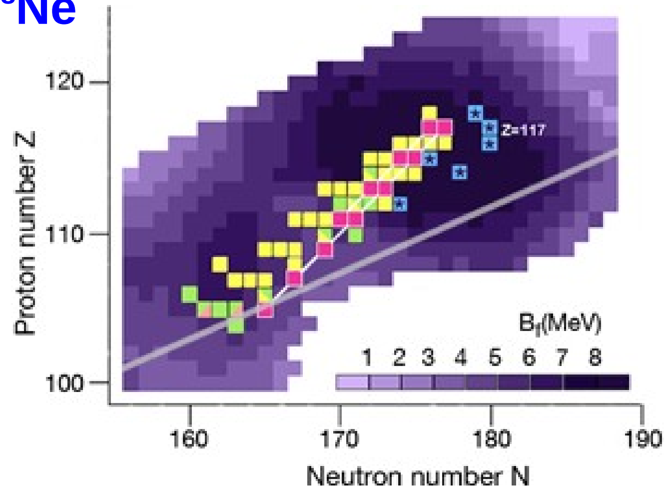
Outlook and Summary

Introduction

- The heaviest elements are synthesized in laboratories by fusion reactions.
- expected fusion enhancement with neutron-rich radioactive nuclei
  - larger r.m.s. radii (skin, halo)
  - collective modes (soft-dipole resonance)
  - exotic shapes
  - neutron transfer
  - etc.

- Neutron-rich radioactive beams may be used for producing neutron-rich isotopes of superheavy element.
- These beams may help reach the predicted N=184 neutron shell closure.

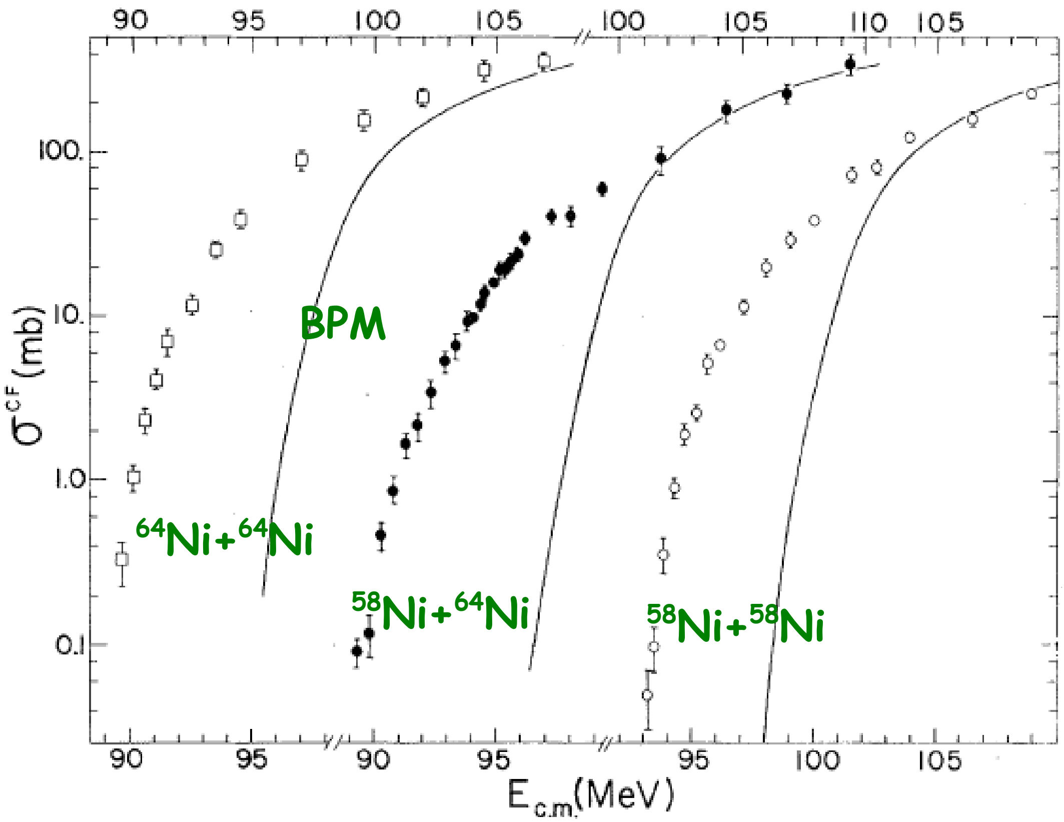
- Nuclear fusion provides power to stars.
- Fusion is predicted to be a heat source in the crust of neutron stars.
  - $^{24}O+^{24}O$, $^{28}Ne+^{28}Ne$

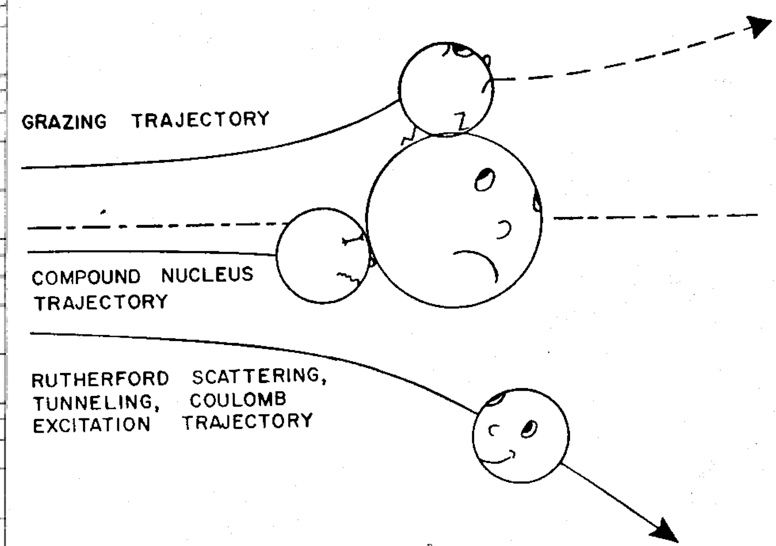


Loveland, PRC76(2007)014612
Horowitz, PRC77(2008)045807

Introduction

- **tunneling**
- **Sub-barrier fusion enhancement**
- **coupling of the intrinsic degrees of freedom to the relative motion**
- **static deformation, surface vibration, nucleon transfer, and so on**

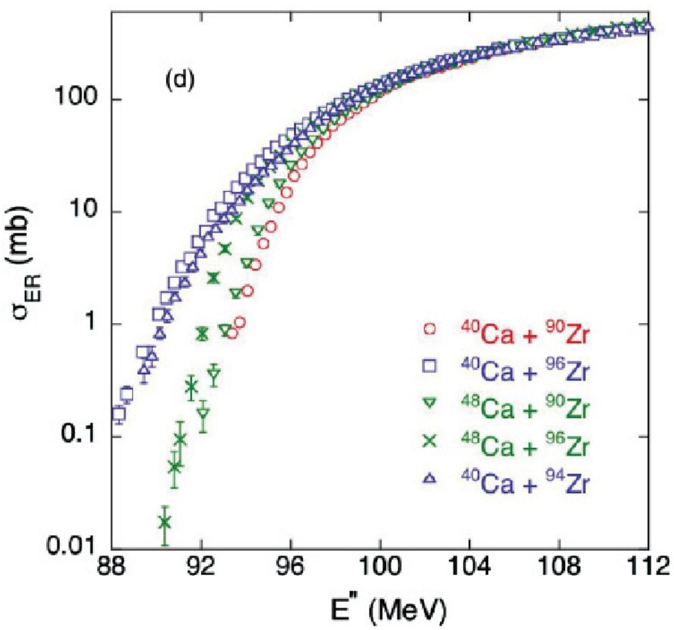


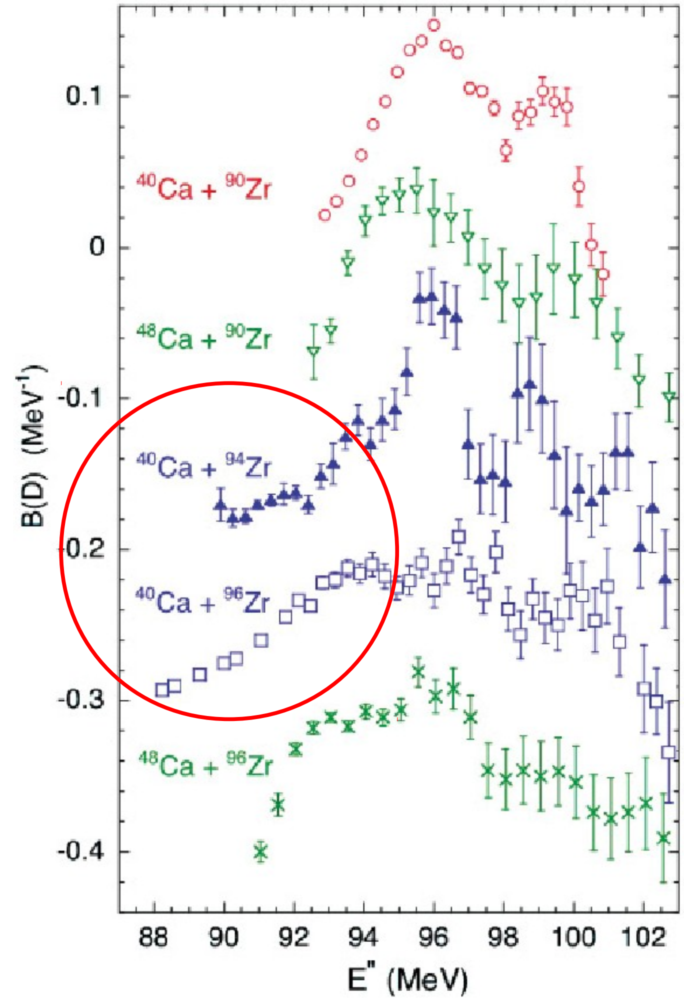


Beckerman et al., PRC25(1982)837

Introduction

neutron transfer





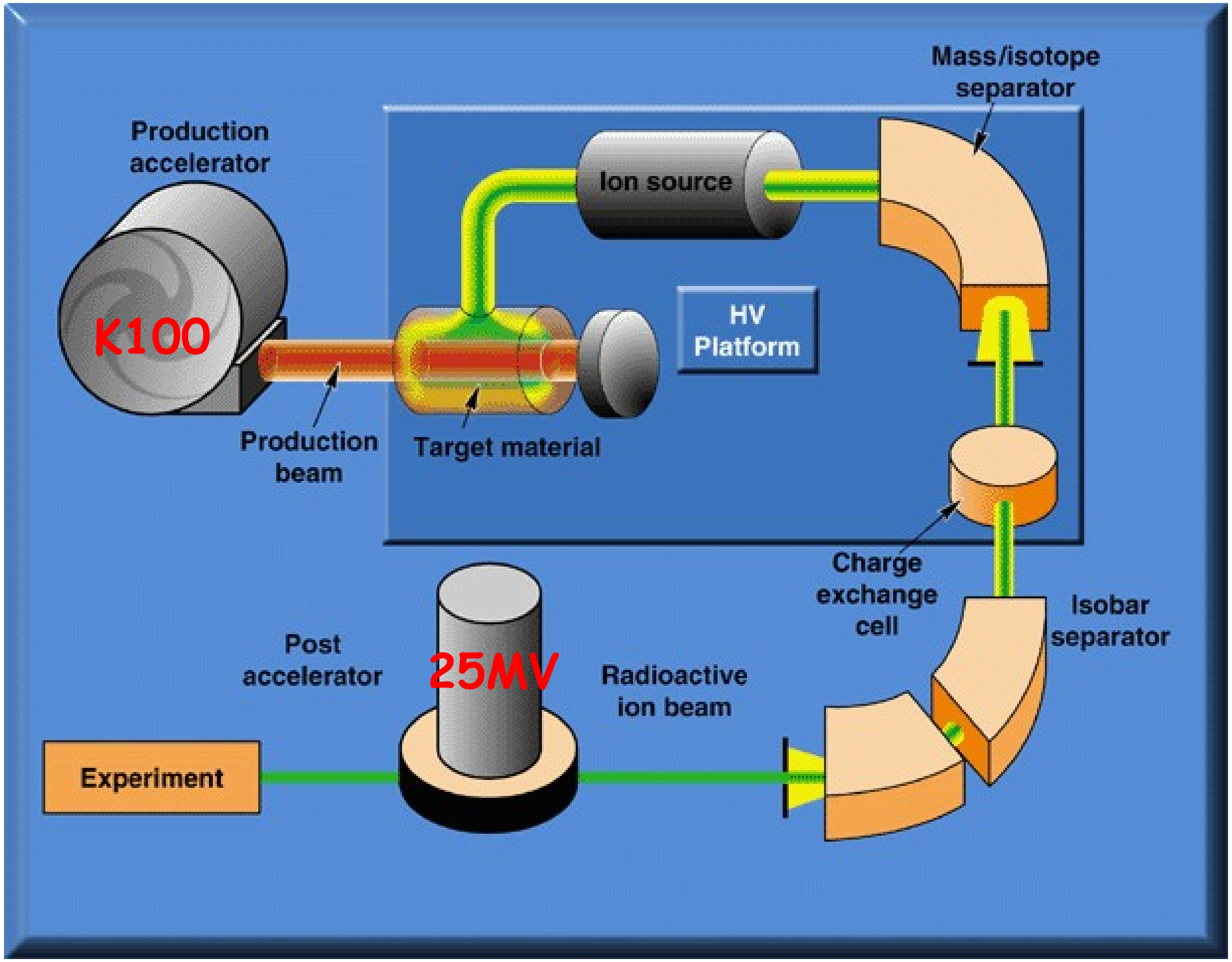
System	$+1n$	$+2n$	$+3n$	$+4n$	$+5n$	$+6n$
^{40}Ca+^{90}Zr	−3.61	−1.44	−5.86	−4.17	−9.65	−9.05
^{40}Ca+^{94}Zr	+0.14	+4.89	+4.19	+8.12	+3.57	+4.65
^{40}Ca+^{96}Zr	+0.51	+5.53	+5.24	+9.64	+8.42	+11.62
^{48}Ca+^{90}Zr	−6.82	−9.79	−17.73	−22.67	−31.93	−37.60
^{48}Ca+^{96}Zr	−2.71	−2.82	−6.63	−8.69	−13.87	−17.00

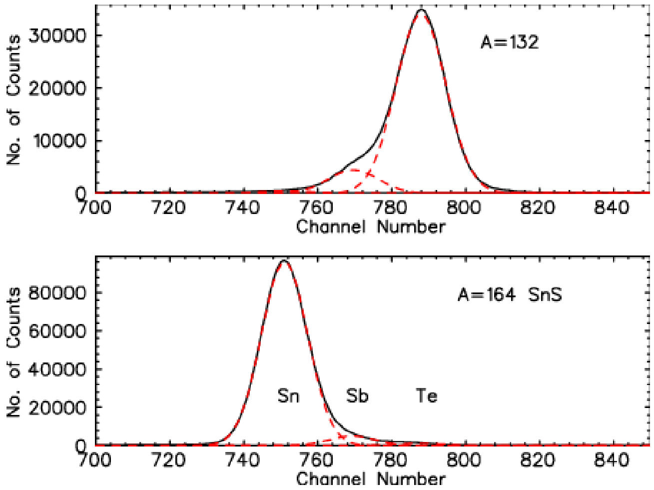
- **Sub-barrier fusion enhancement correlates with +Q-values for transfer.**
- **The barrier distributions for ^{40}Ca+^{94,96}Zr have a low energy tail.**
- **N-rich radioactive nuclei induced fusion**

Stefanini et al., PRC76(2007)014610

HRIBF Beams

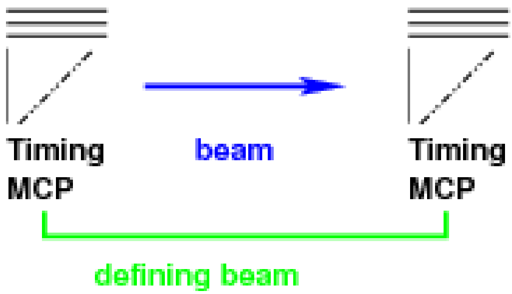
- ISOL
- ^{238}UC(p,FF)
- ~5 MeV/u for A~130
- Isobar purification by selecting SnS
- Cs vapor charge exchange cell to obtain negative ions
- maximum intensity on target ~ 200k ^{132}Sn/s

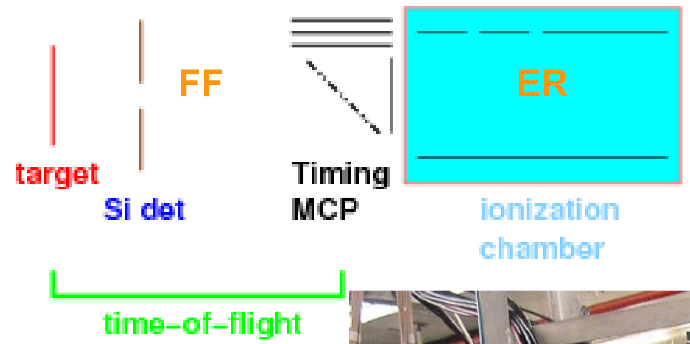




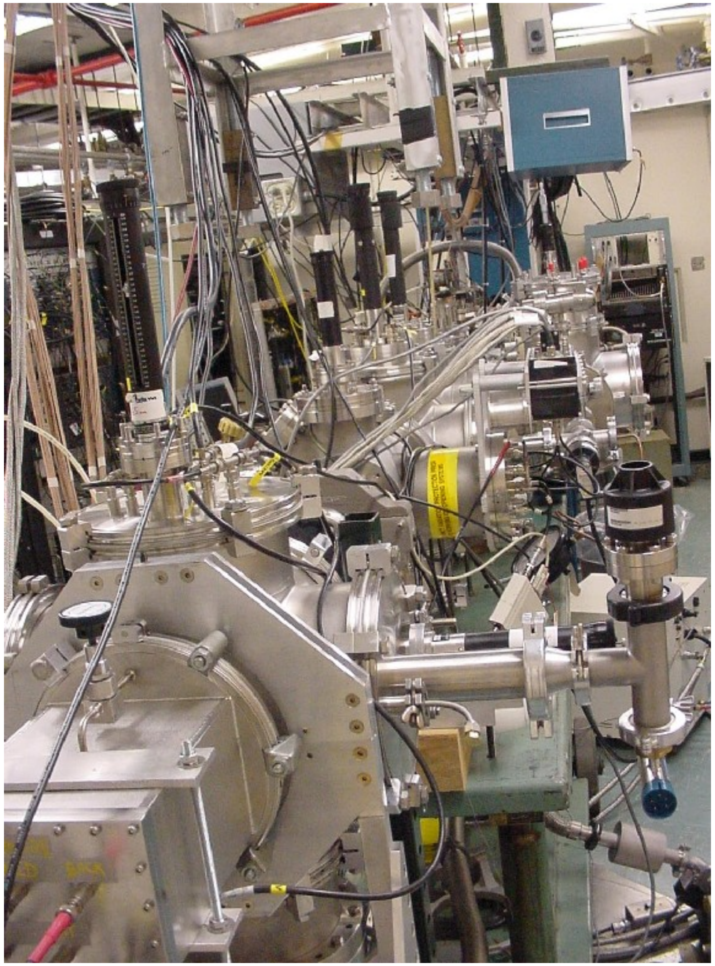
http://www.phy.ornl.gov/hribf/

Apparatus

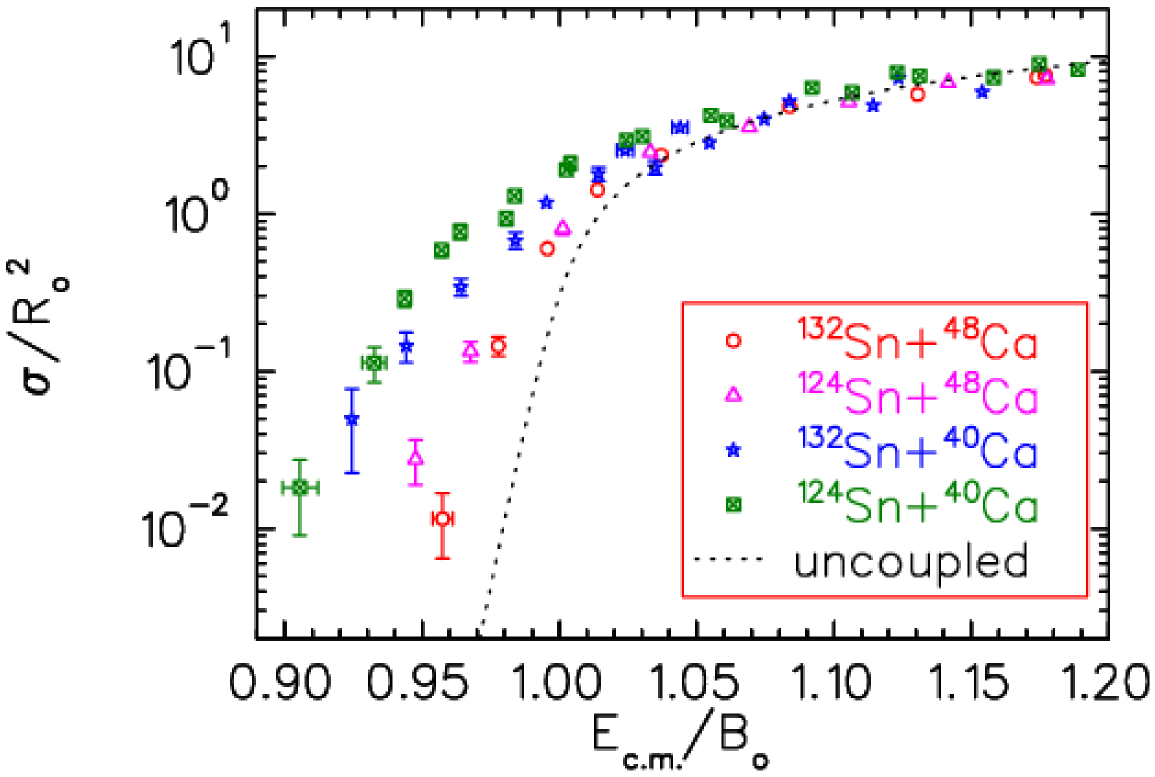




- Experiments used Ca and Ni targets
- Inverse kinematics (heavy projectile on light target)
- Reaction products forward focusing
- Detecting ER and beam in the IC simultaneously at 0°
- ER identification by time-of-flight and E-ΔE
- Detecting FF by an annular double-sided Si strip detector
- thick targets to compensate for the low intensity beams



Results: Sn+Ca



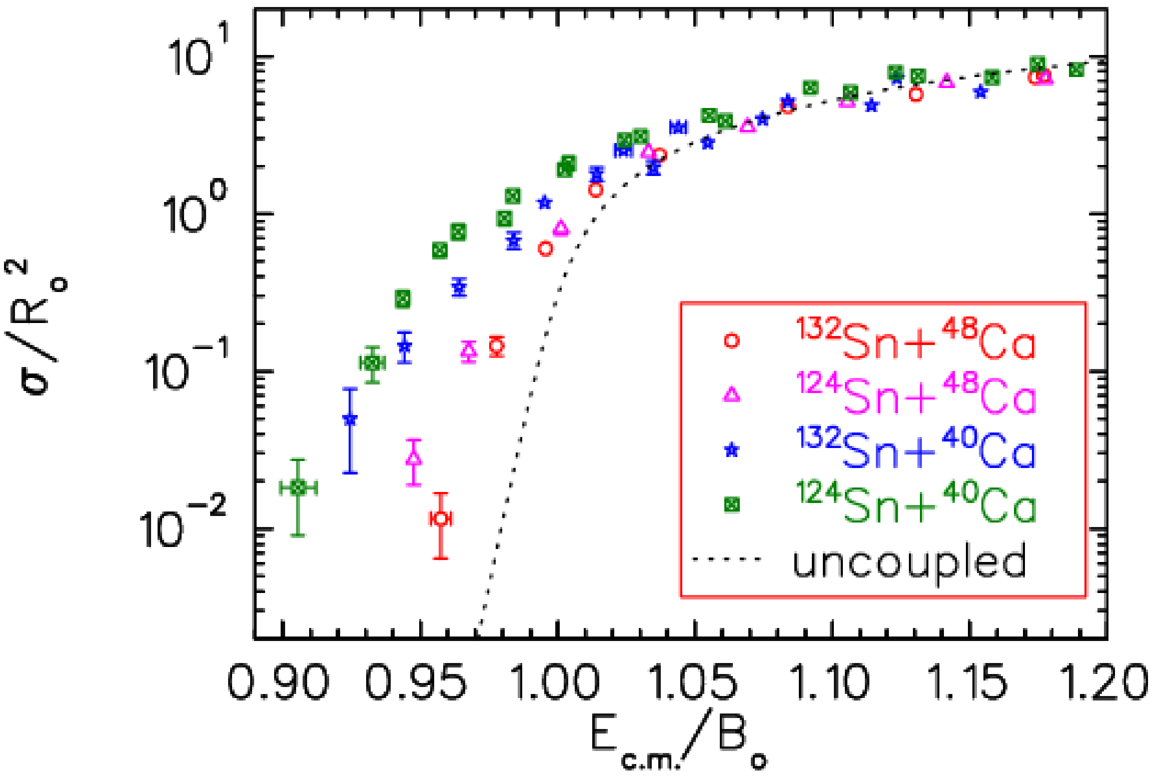
$$R_o = A_p^{1/3} + A_t^{1/3}$$

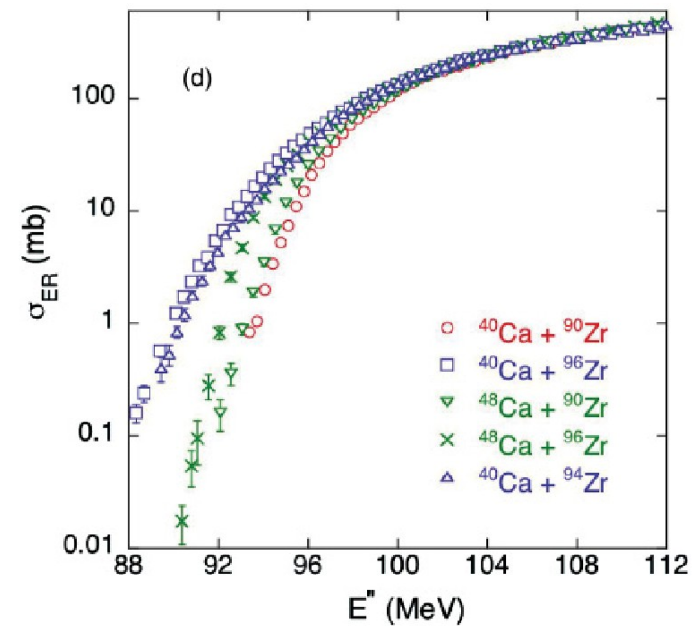
$$B_o = Z_p Z_t / R_o$$

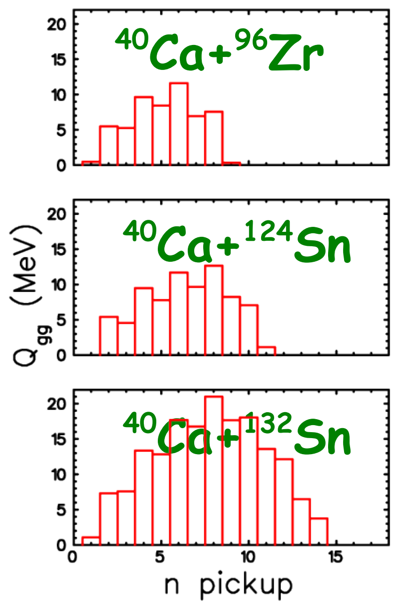
- Compare reduced excitation functions to remove differences in nuclear size and barrier height.
- enhancement from inelastic excitations of projectile and target w.r.t. the no coupling calculations
- The enhancement for reactions with ^{40}Ca is larger than that with ^{48}Ca because of the 3^- state in ^{40}Ca.
- The enhancement for reactions with ^{132}Sn is smaller than that with ^{124}Sn because ^{132}Sn is doubly magic and less collective.

Kolata et al., submitted to PRC

Results: Sn+Ca

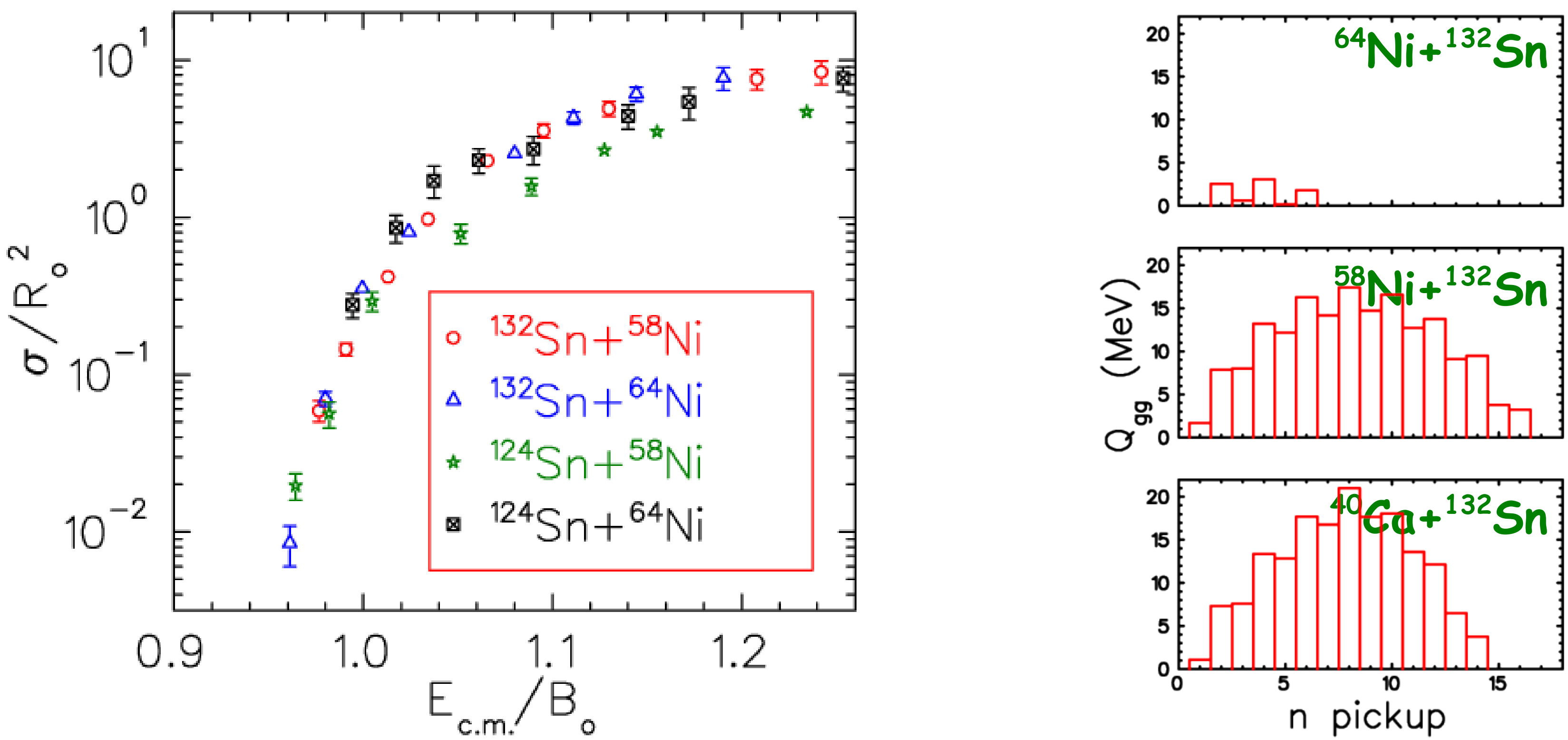






- The Q-value for transfer is negative in reactions with ^{48}Ca.
- comparison similar to ^{40}Ca+^{90,96}Zr
- suggests enhancement due to inelastic excitations and transfer in reactions with ^{40}Ca

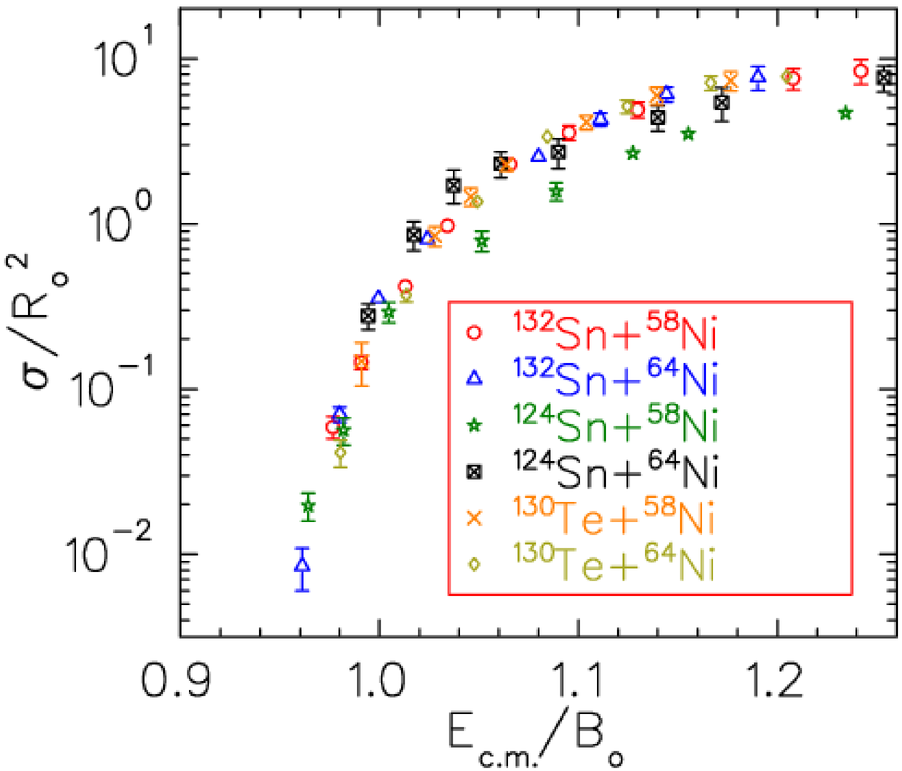
Results: Sn+Ni

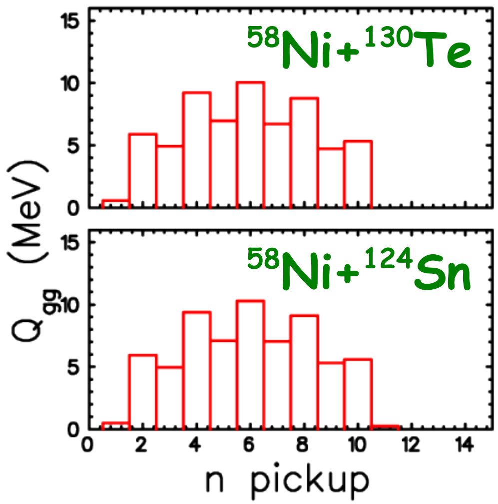


- The magnitude of sub-barrier enhancement in $^{132}Sn+^{58}Ni$ resembles that in other Sn+Ni. (no isotope dependence)
- The influence of neutron transfer is not as pronounced as in $Sn+^{40}Ca$.

Liang et al., PRC75(2007)054607
Kohley et al., PRL107(2011)202701

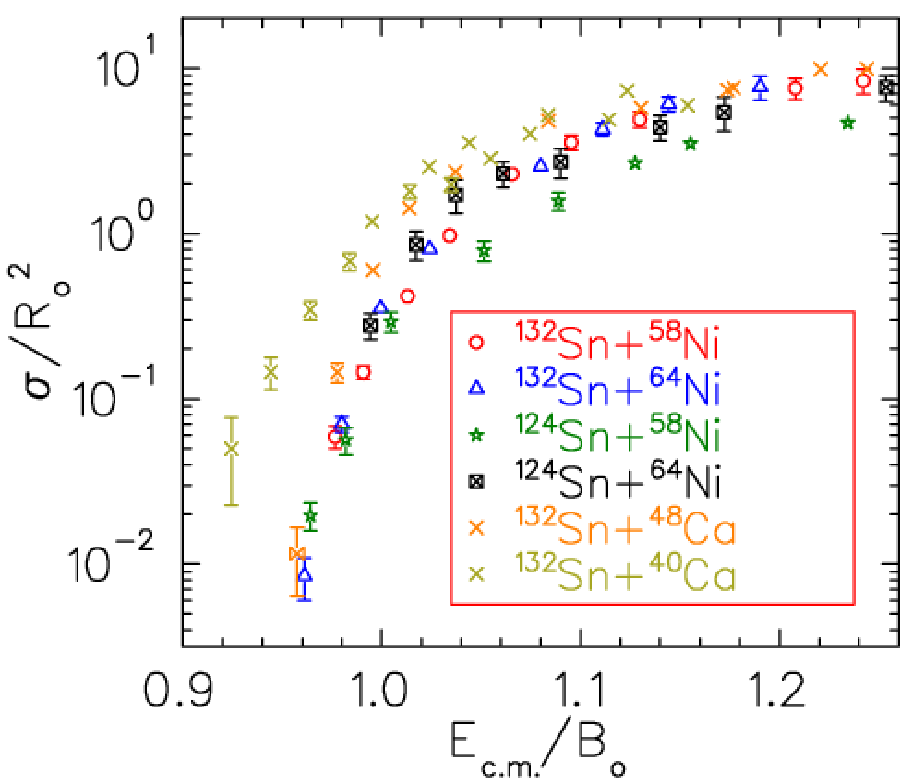
Results: Te+Ni

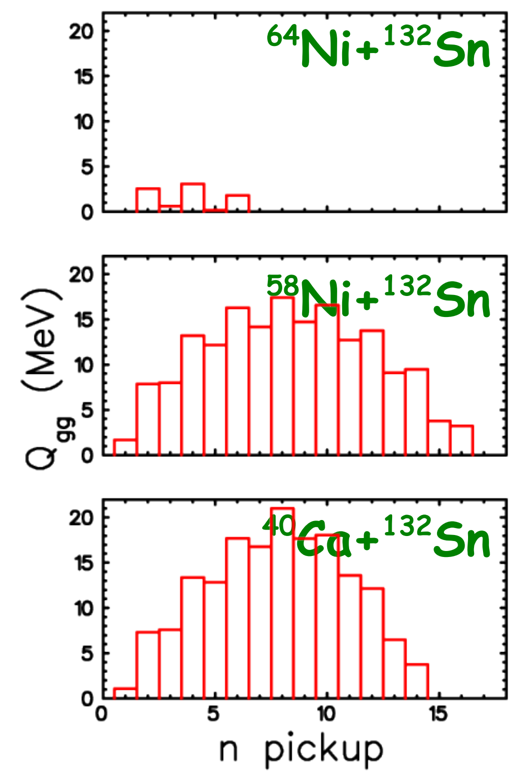




a similar behavior for the comparison of ^{130}Te+^{58,64}Ni

Results: Sn+Ni





- The magnitude of sub-barrier enhancement in $^{132}Sn+^{58}Ni$ resembles that in other Sn+Ni. (no isotope dependence)
- The influence of neutron transfer is not as pronounced as in $Sn+^{40}Ca$.

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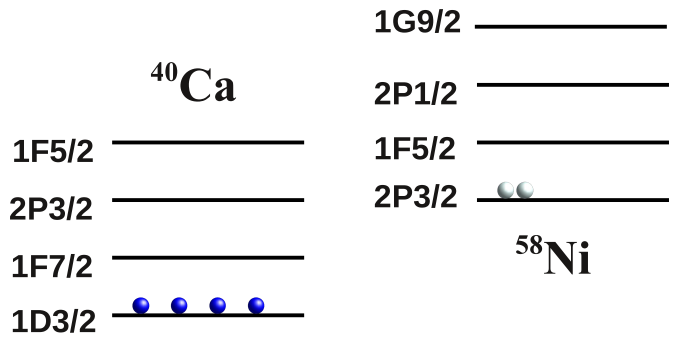
Comparisons of Sn+^{40}Ca and Sn+^{58}Ni

Sn+Ca: Z_pZ_t = 1000

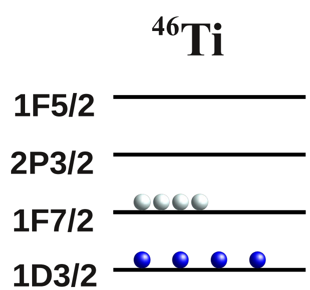
Sn+Ni: Z_pZ_t = 1400, deep inelastic collisions?



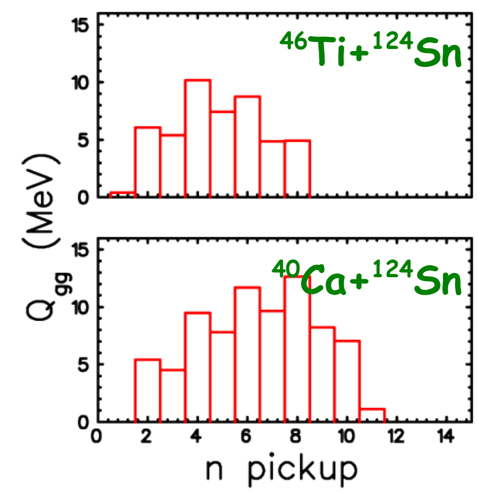
	^{32}S	^{40}Ca	^{58}Ni
E_3-	5.006	3.737	4.475
β_3-	0.40	0.43	0.19

measure fusion excitation functions for ^{124}Sn+^{46,50}Ti

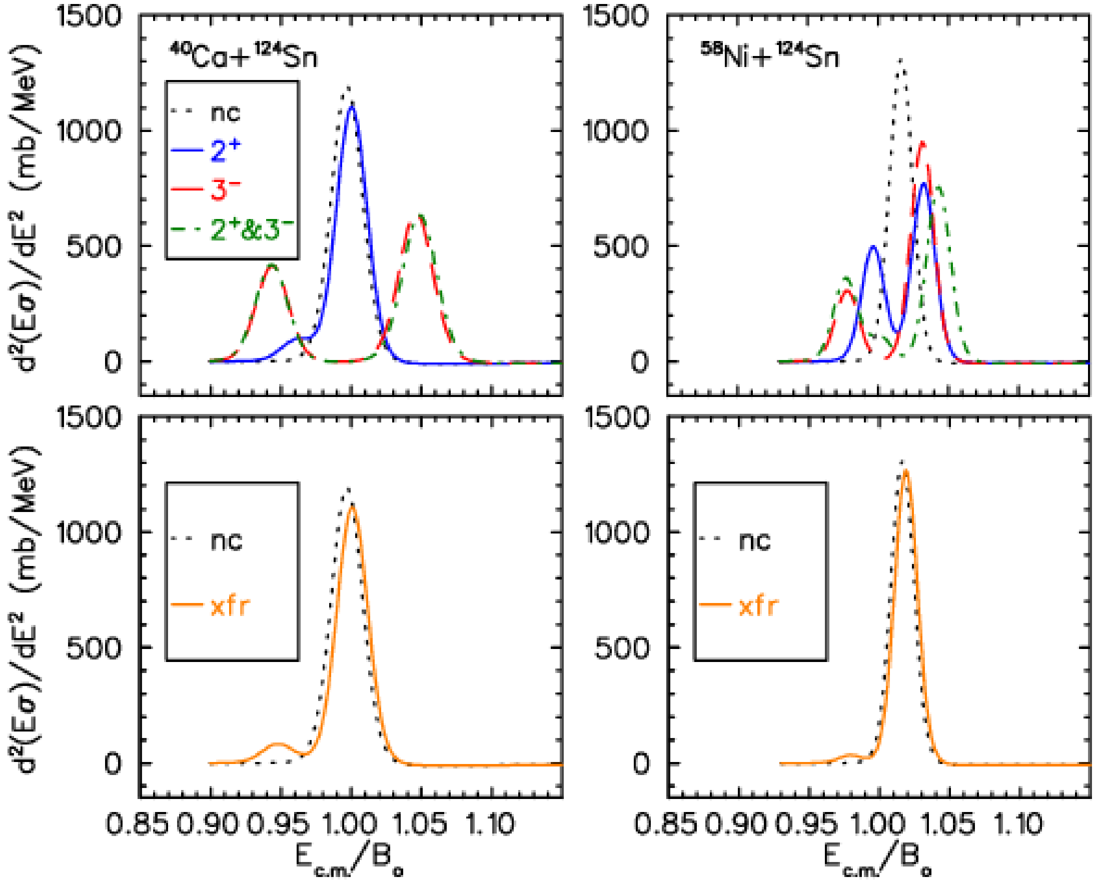
Z_pZ_t = 1100



	^{46}Ti	^{50}Ti
E_3-	3.058	4.410
β_3-	0.142	0.138



Coupled-Channels Analysis



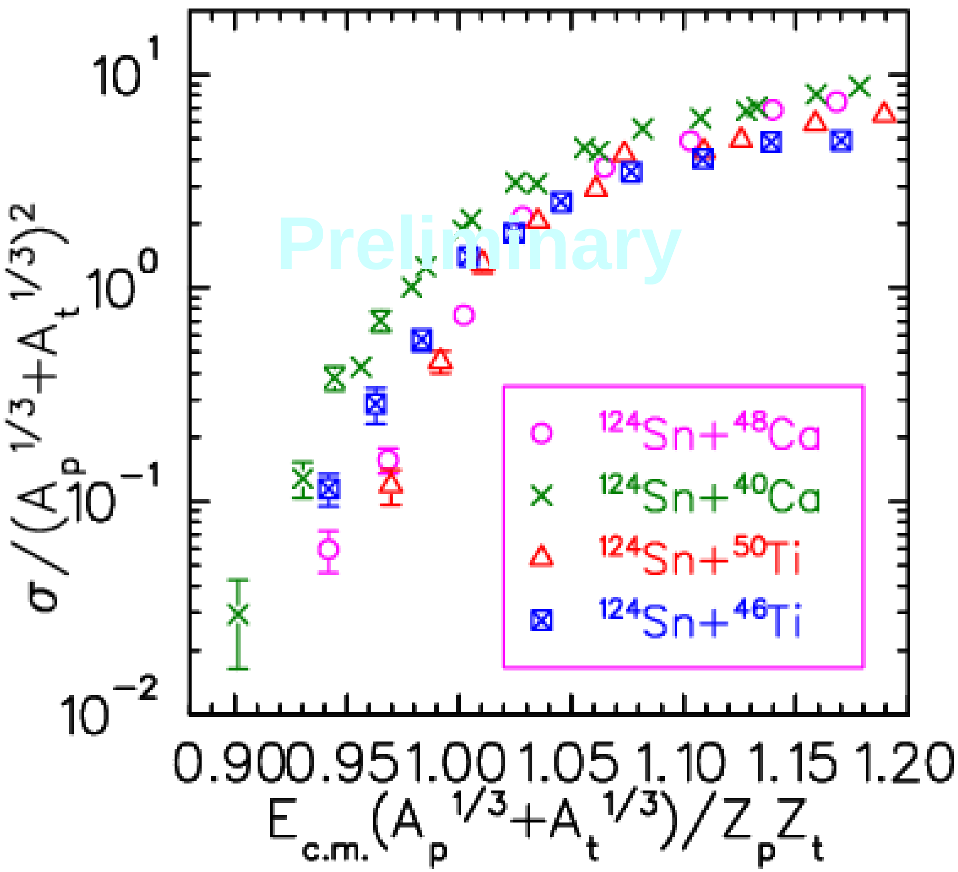
	^{32}S	^{40}Ca	^{58}Ni
E_{3^-}	5.006	3.737	4.475
β_{3^-}	0.40	0.43	0.19

- The peak position of the low energy barrier originated from coupling to the excitation of the 3^- state of Ca is much lower than that of Ni.
- The barrier resulted from coupling to transfer overlaps with that from coupling to the excitation of the 3^- state of Ca.
- The role of coupling to high-lying 3^- states

Rowley & Hagino, NPA834(2010)110c
Sonzogni et al., PRC57(1998)722

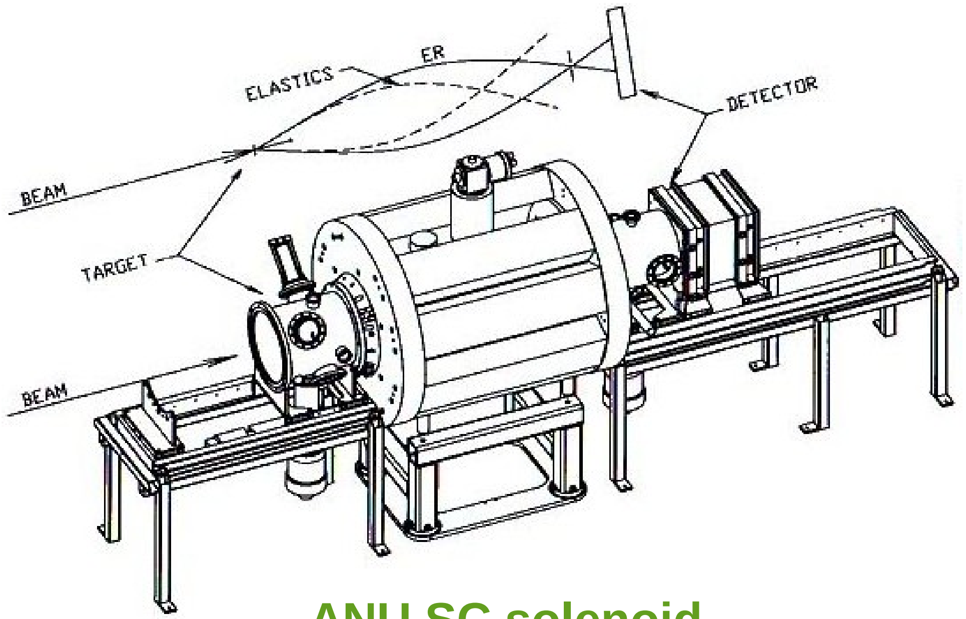
Fusion of $^{46,50}Ti+^{124}Sn$

Compare $^{46,50}Ti+^{124}Sn$ with $^{40}Ca+^{124}Sn$ (Legnaro)



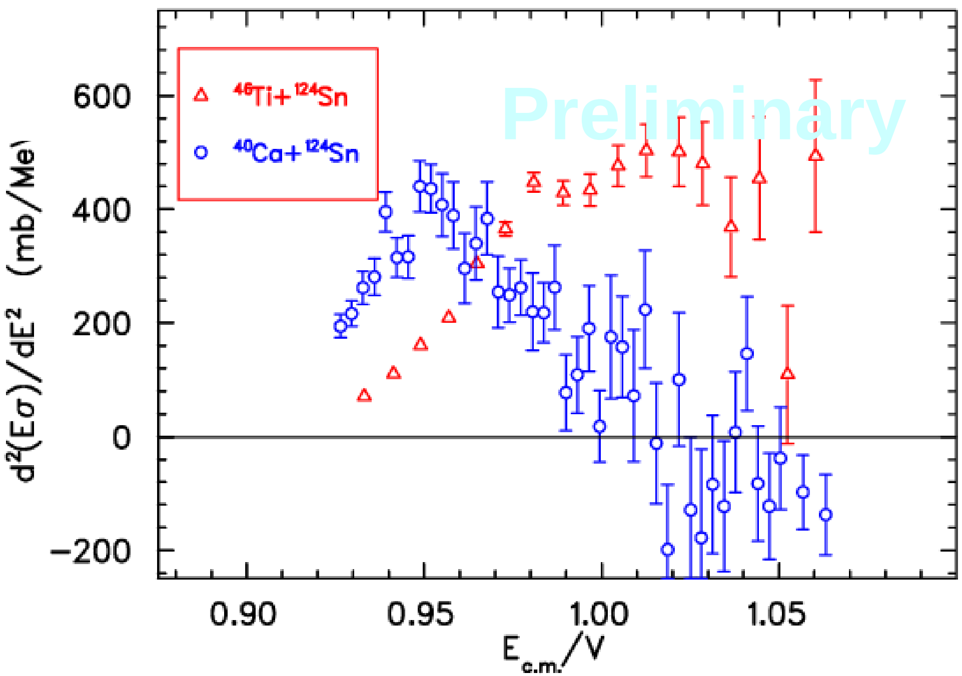
F Scarlassara et al., NPA672(2000)99

Fusion of $^{46,50}Ti+^{124}Sn$



ANU SC solenoid

Comparison of the barrier distributions for $^{40}Ca+^{124}Sn$ (Legnaro) with $^{46}Ti+^{124}Sn$



- Compare barrier distributions calculated by coupled-cahhnels
- Measure neutron transfer for $^{46}Ti+^{124}Sn$

F Scarlassara et al., NPA672(2000)99

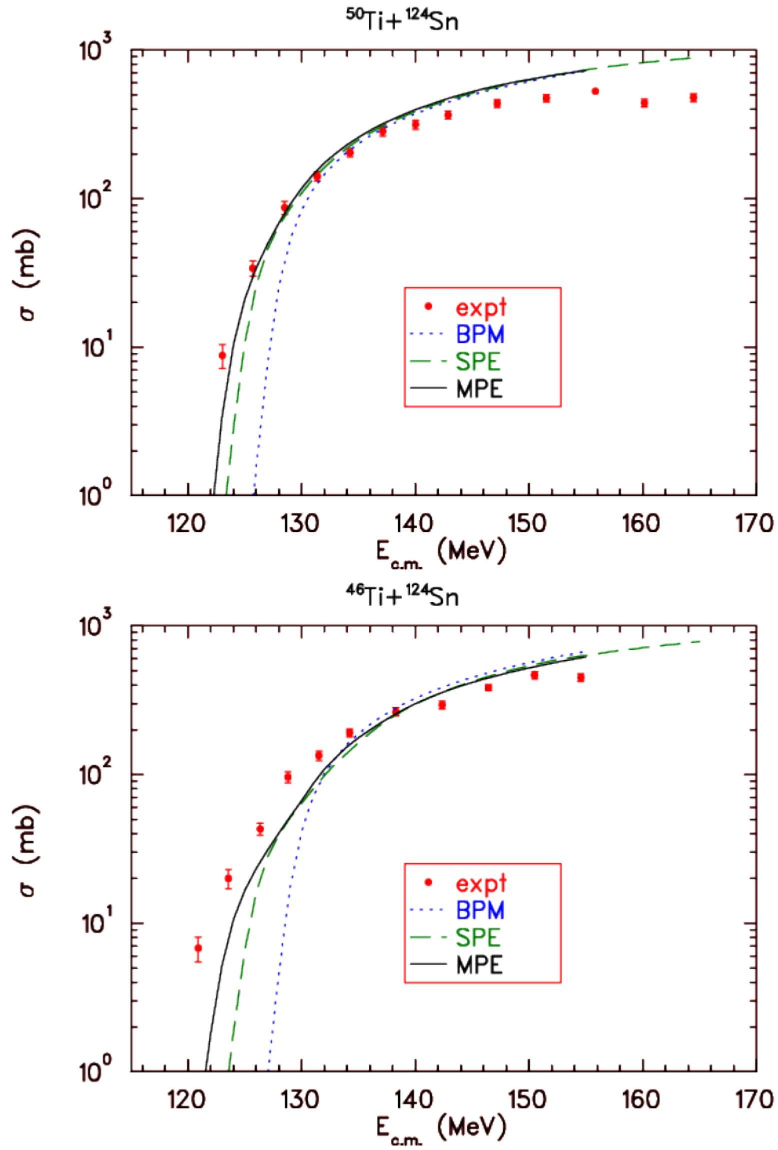
Summary

- Fusion excitation functions have been measured using neutron-rich radioactive Sn and Te on Ca and Ni targets.
- A large sub-barrier fusion enhancement has been observed in reactions with ^{40}Ca.
- Comparing to the fusion with ^{48}Ca, the enhancement in ^{40}Ca can be attributed to neutron transfer.
- The Q-values for multineutron transfer in ^{132}Sn+^{58}Ni are comparable to those in ^{132}Sn+^{40}Ca but the enhancement is smaller.
- Data analysis is in progress for the high precision measurement of fusion excitation function for ^{124}Sn+^{46}Ti to deduce the barrier distribution.

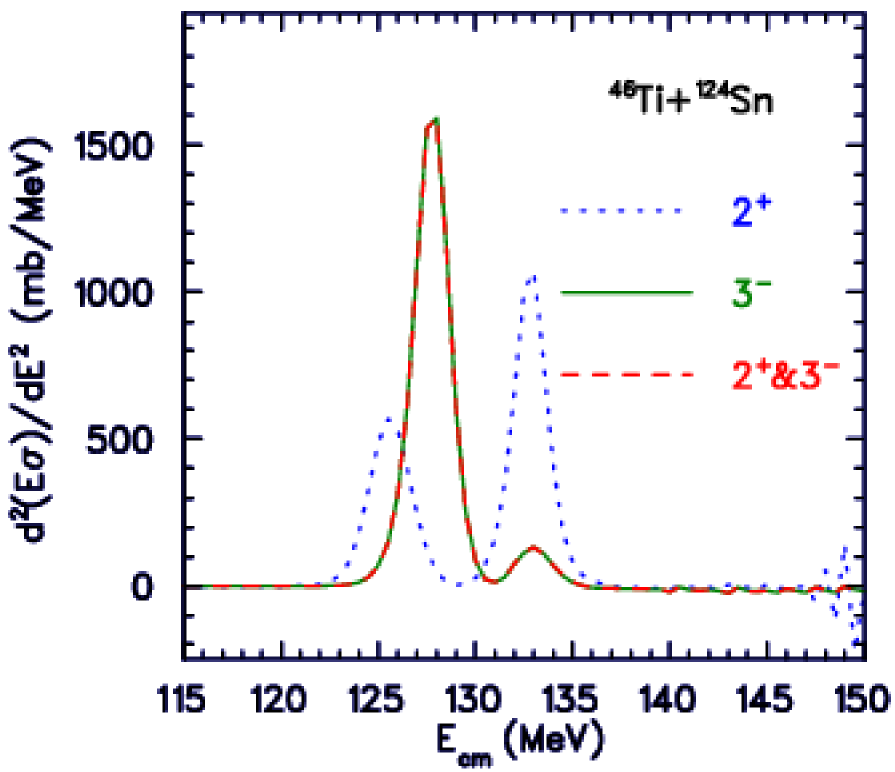
Collaborators

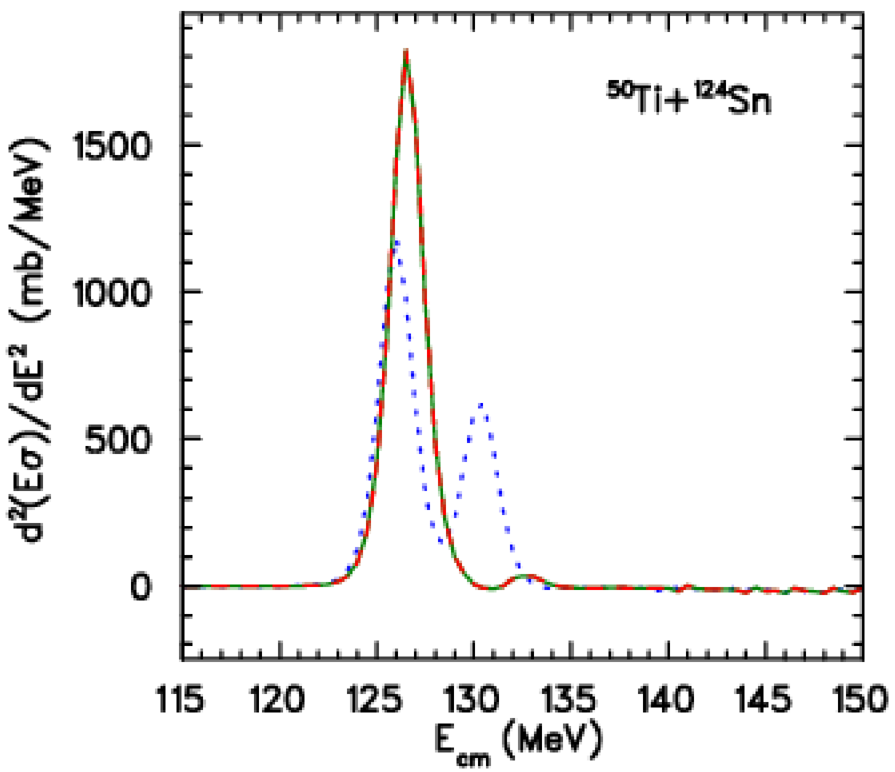
CJ Gross, Z Kohley, D Shapira, RL Varner, JM Allmond, K Lagergren, PE Mueller – ORNL
JJ Kolata, A Howard, A Roberts, A Villano – University of Notre Dame
AL Caraley – SUNY at Oswego
W Loveland – Oregon State University
M Dasgupta, DJ Hinde, E Williams, ML Brown, IP Carter, M Evers, DH Luong, A Wakhle – Australian National University

Backup Slides



Backup Slides





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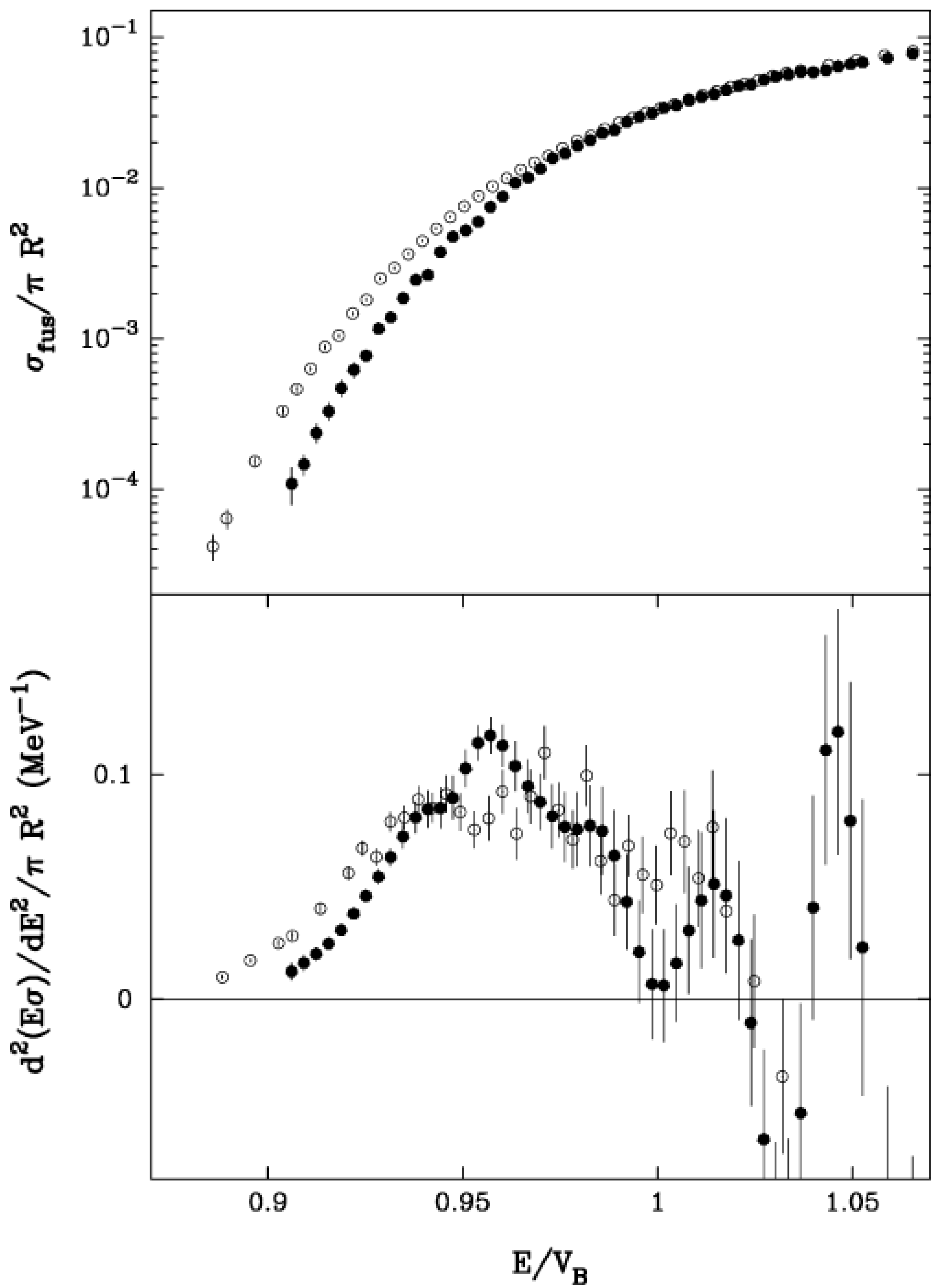

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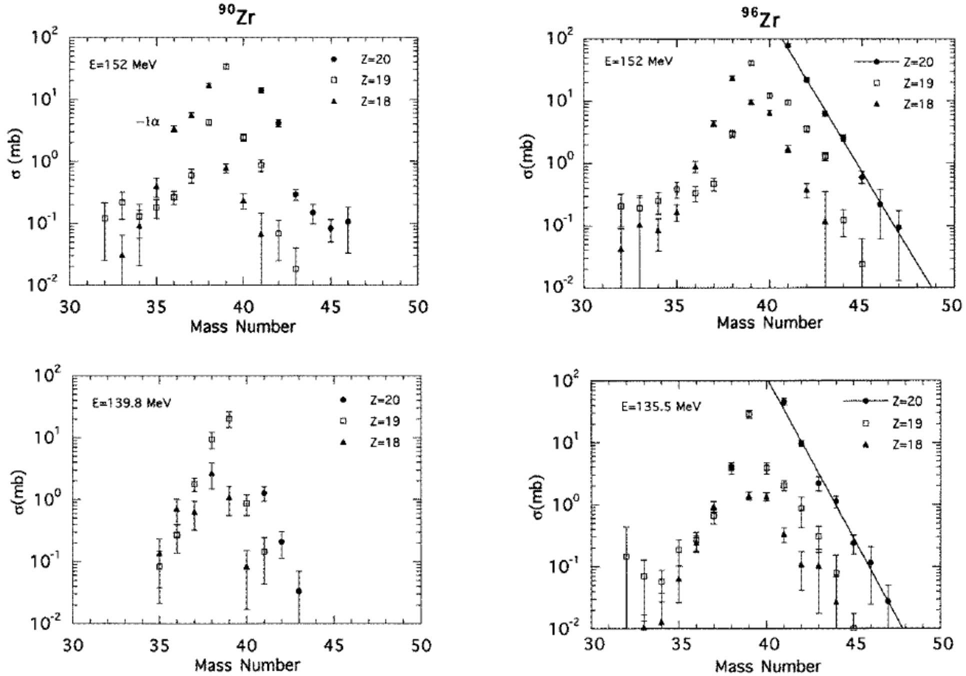

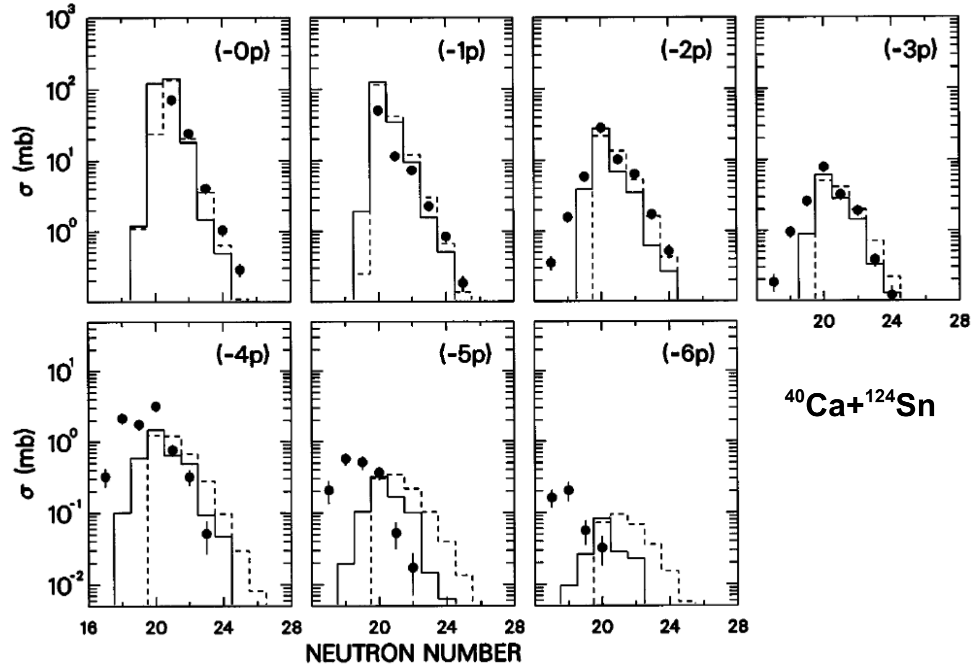

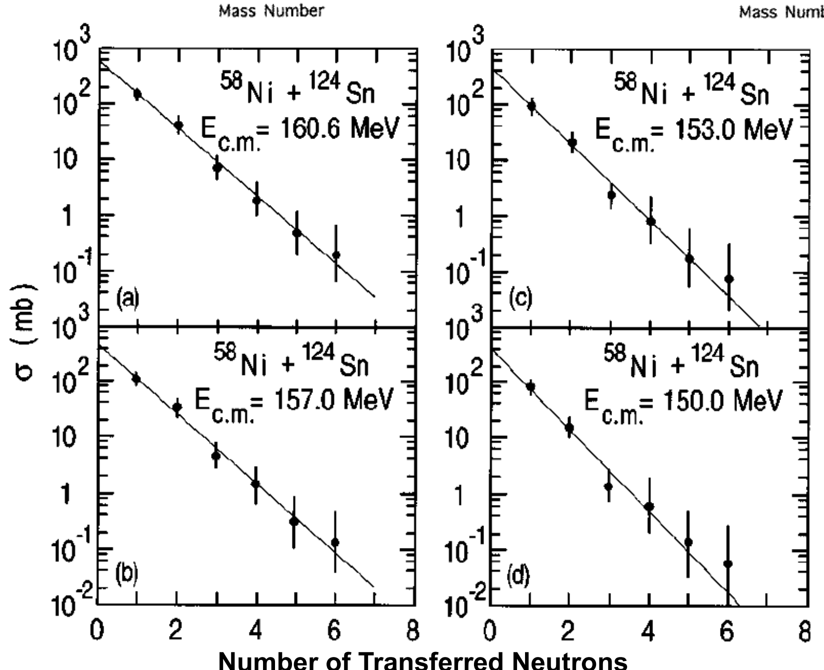

- **Transfer has been measured for ^{40}Ca+^{90,96}Zr, ^{40}Ca+^{124}Sn, and ^{58}Ni+^{124}Sn.**
- **Neutron transfer has large cross sections near the barrier.**
- **Transfer cross sections for ^{40}Ca+^{90}Zr are small as expected from the Q-values.**

Montagnoli et al., JPG23(1997)1431
Corradi et al., PRC54(1996)201
Jiang et al., PRC57(2098)2393