Fusion of Neutron-Rich Radioactive ^{132,134}Sn with ^{64}Ni

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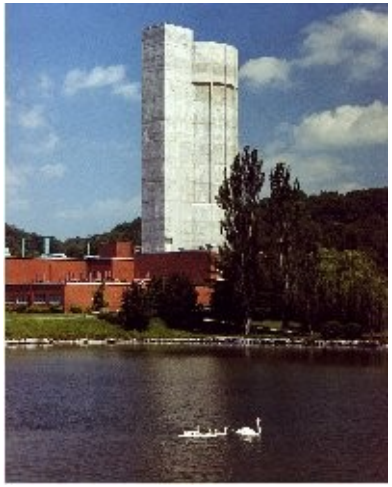

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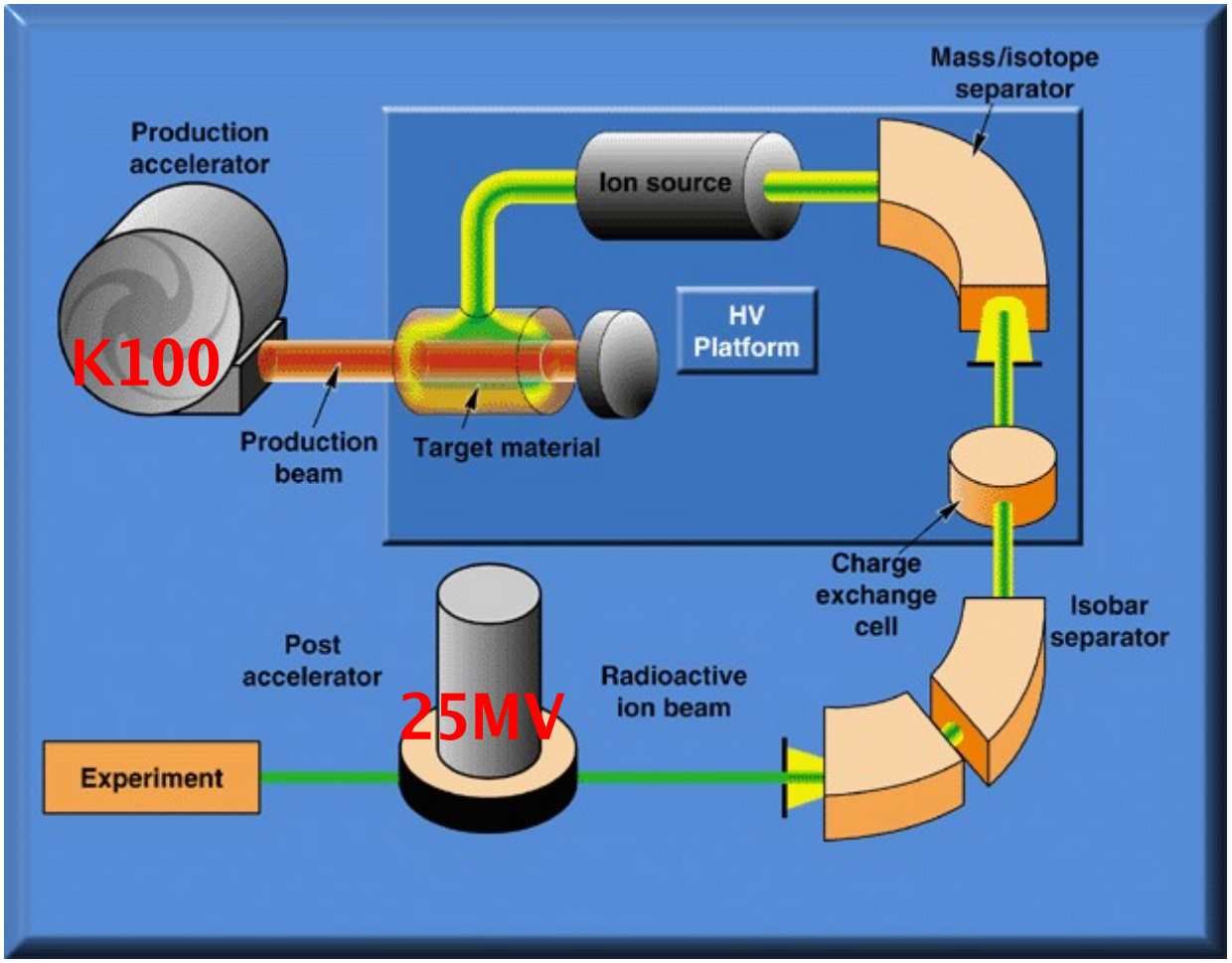
Introduction

- The heaviest elements are produced by fusion reactions with very low cross sections.
- It is predicted that fusion near the Coulomb barrier would be enhanced in reactions induced by neutron-rich radioactive beams.
- This is in part due to the larger radius of the n-rich nucleus lowering the barrier.
- A large number of neutron transfer can also contribute to the enhancement.
- The compound nucleus made in such reactions is likely to have a higher survival probability.
- This would allow the study of chemical properties of new n-rich heavy nuclei.
- Report on the fusion measurements performed with radioactive ^{132,134}Sn beams produced at HRIBF.

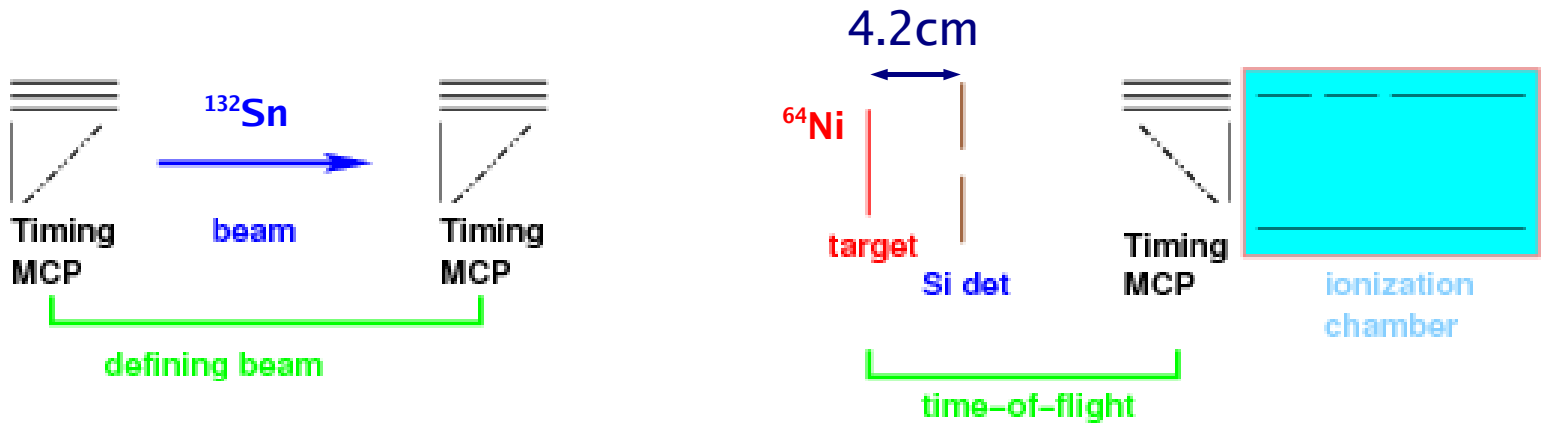
Radioactive ^{132}Sn beam production

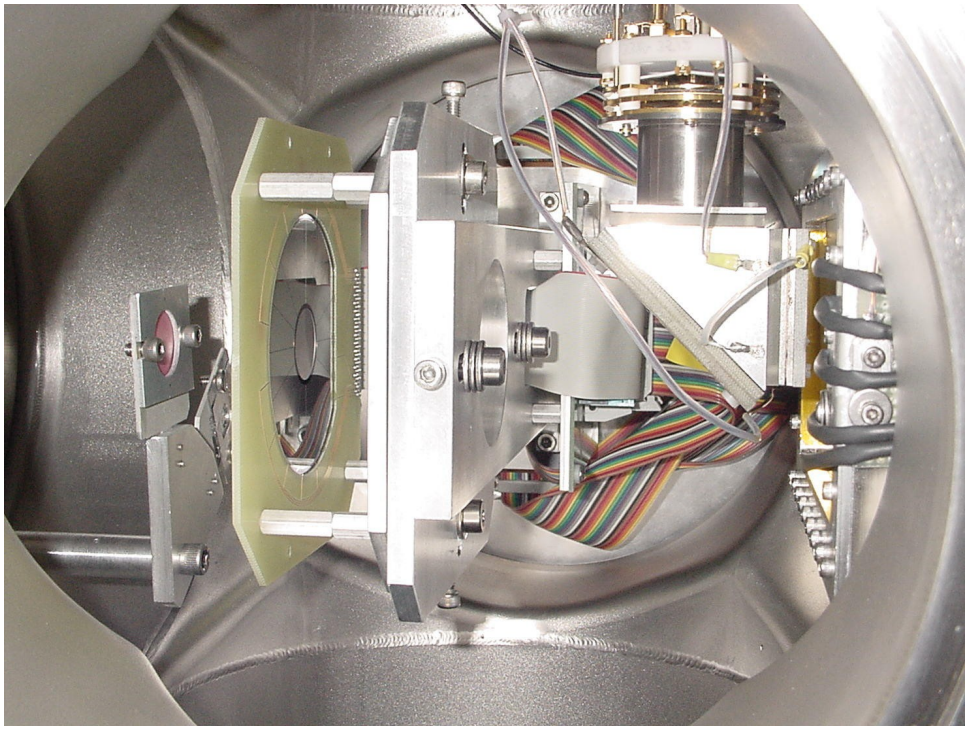
- ISOL
- 40 MeV proton on UC target
- fission fragments
- Isobar purification by S
- SnS^+ breakup in charge exchange cell
- double stripping
- ~96% ^{132}Sn
- Intensity:
  - average 50k pps
  - maximum 72k pps



Only HRIBF can provide post-accelerated fission-fragment beams to energies above the Coulomb barrier at present.

Apparatus





Evaporation Residue

- Time-of-flight: MCPs
- E-ΔE (Z): Ionization Chamber
- 20 cm from the target

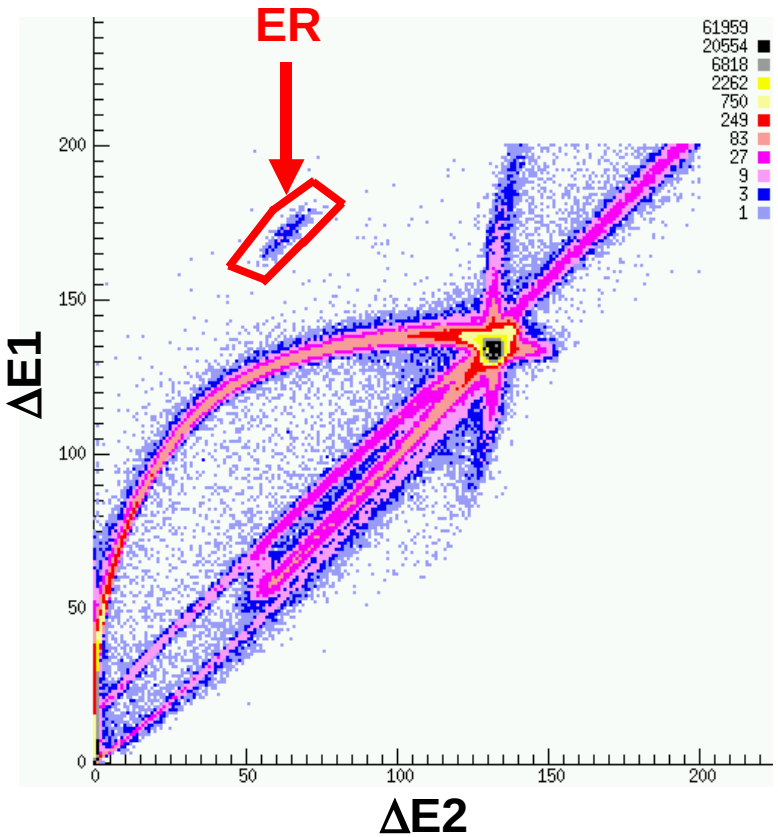
Fission

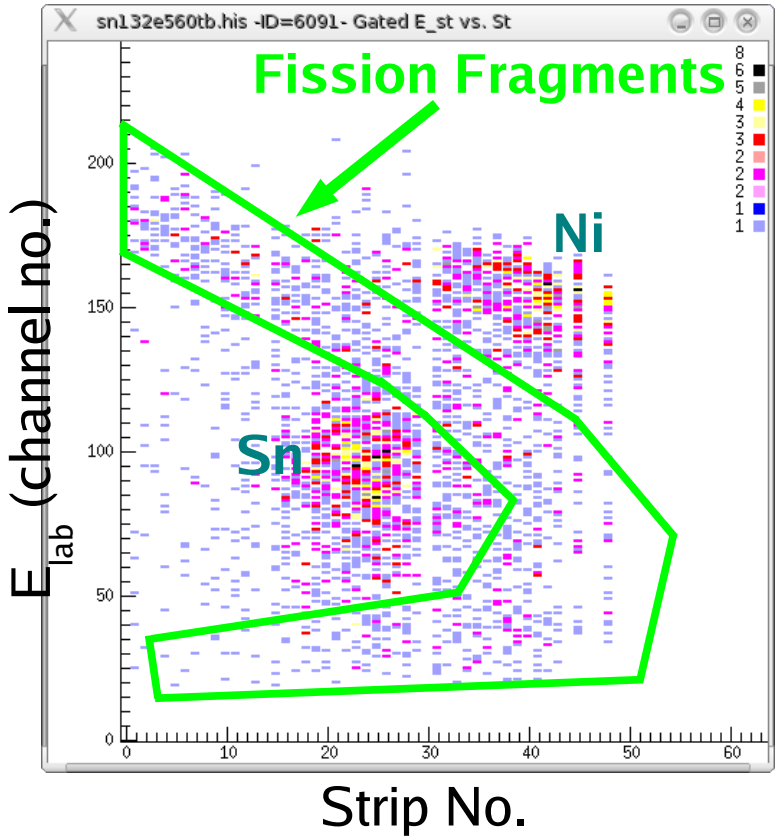
- Frag-frag coincidence
- Micron Semiconductor S2
- 48 concentric strips
- 16 pie-shaped sectors
- 4.2 cm from the target
- θ range 15°-43°

1 mg/cm^2 ^{64}Ni target

Raw Data

560 MeV $^{132}Sn+^{64}Ni$



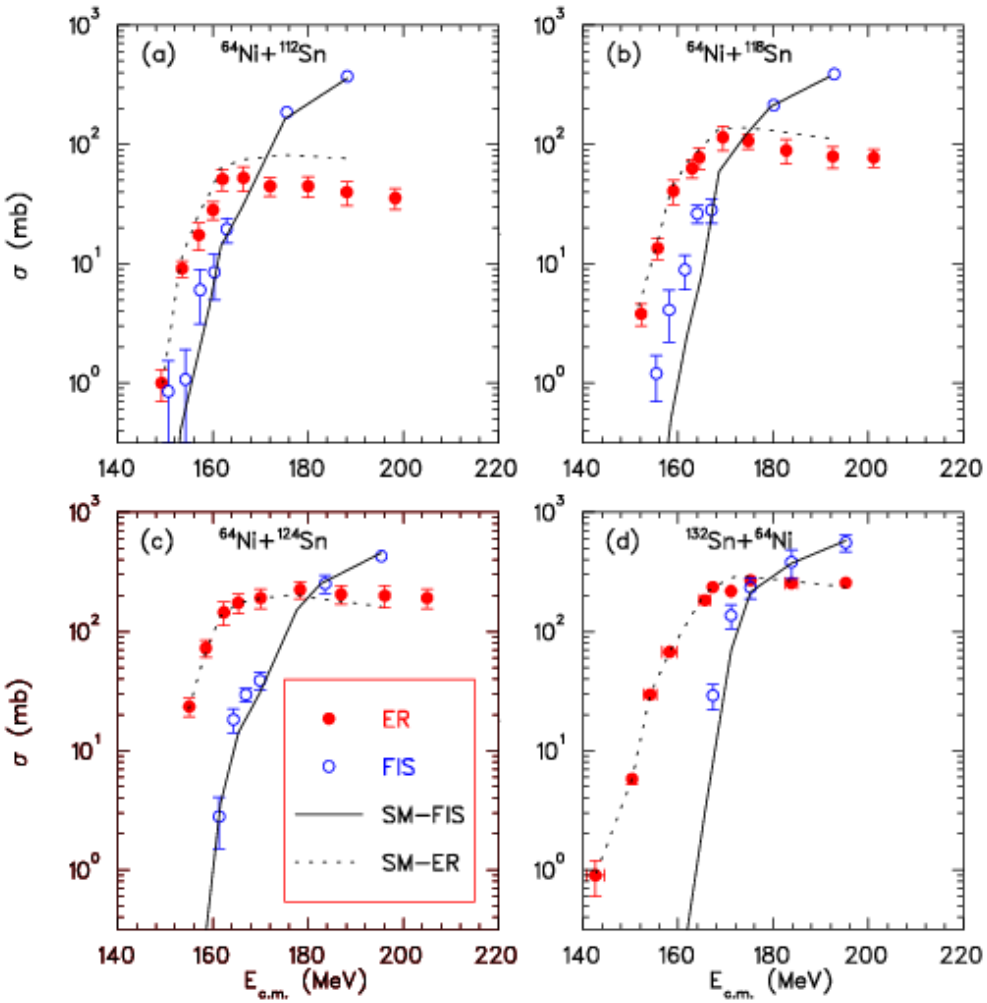


coincidence events
folding angle analysis

- **normalize to the integrated beam in the ion chamber**
- **efficiency for measurements of ER ~95%, fission ~4.5%**

ER and Fission Cross Sections

- compare measurements with statistical model PACE2 calculations



$a = A/8\ \mathrm{MeV}^{-1}$

$a_f/a_n = 1.04$

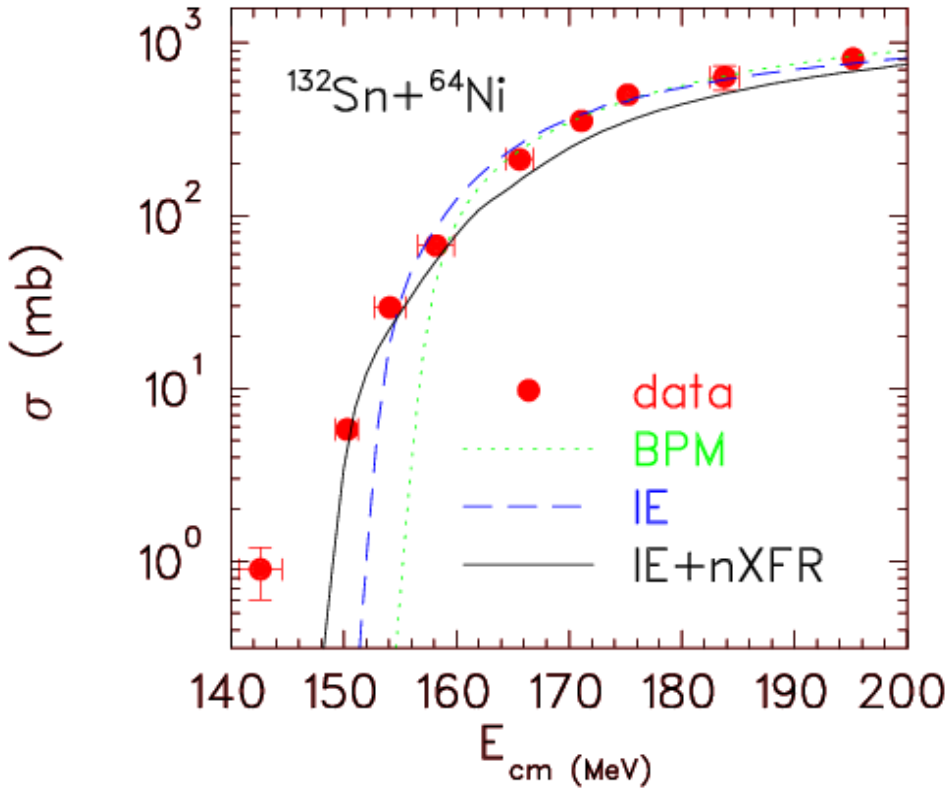
Sierk's fiss. Barrier

$d = 4\ \hbar$

WS Freeman et al., PRL50(1983)1563.
KT Lesko et al., PRC34(1986)2155.

Fusion Cross Section

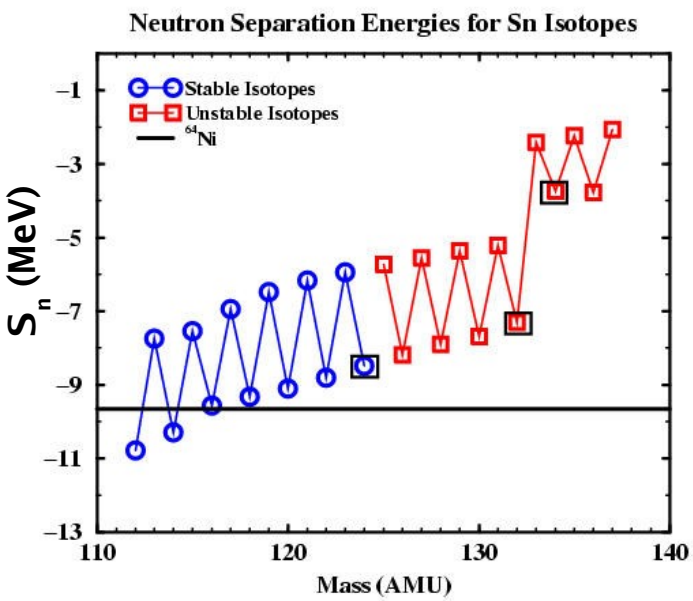
$\sigma_{fus} = \sigma_{ER} + \sigma_{fis}$

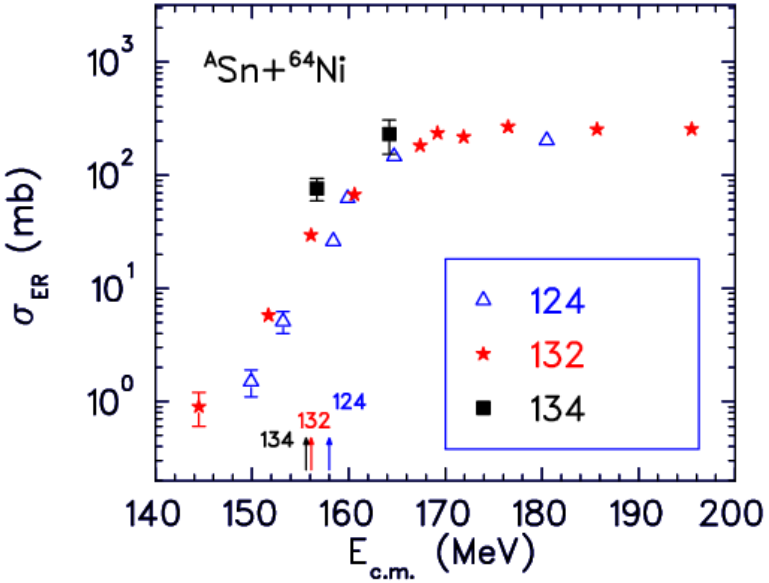


CCFULL

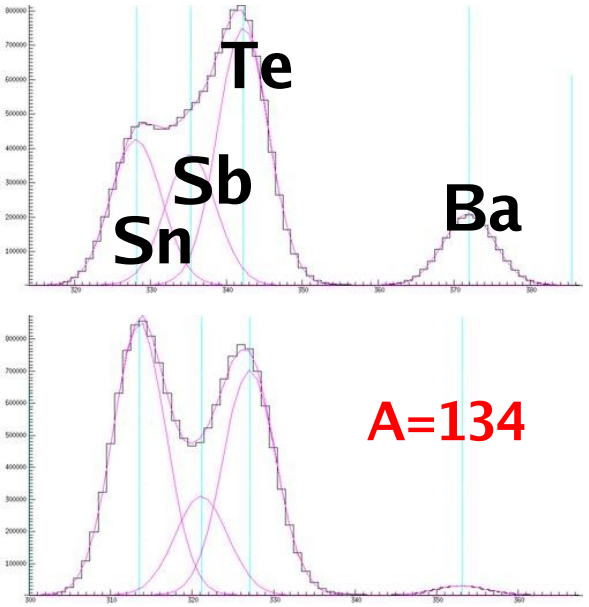
- Sub-barrier fusion is significantly enhanced with respect to a one-dimensional barrier penetration model prediction.
- The Coupled-Channel calculation including inelastic excitation of Sn and Ni overpredicts cross sections near the barrier but underpredicts cross sections below the barrier.
- The CC calculation including inelastic excitation and transfer is in good agreement with the data except for the lowest energy.

Fusion Induced by ^{134}Sn



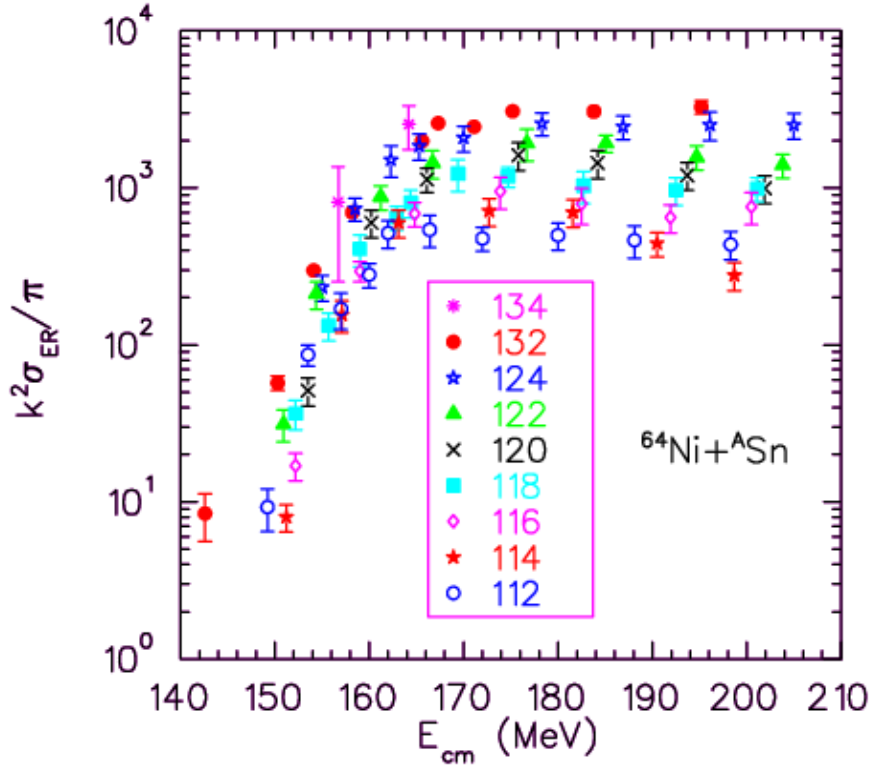


- $B_n(^{132}Sn) = 7.30$ MeV
- $B_n(^{134}Sn) = 3.74$ MeV
- neutron transfer
- Measure Te induced reaction separately.
- Sn/Sb induced ER can be disentangled by repeating runs with different ratios of Sn/Sb in the beam.



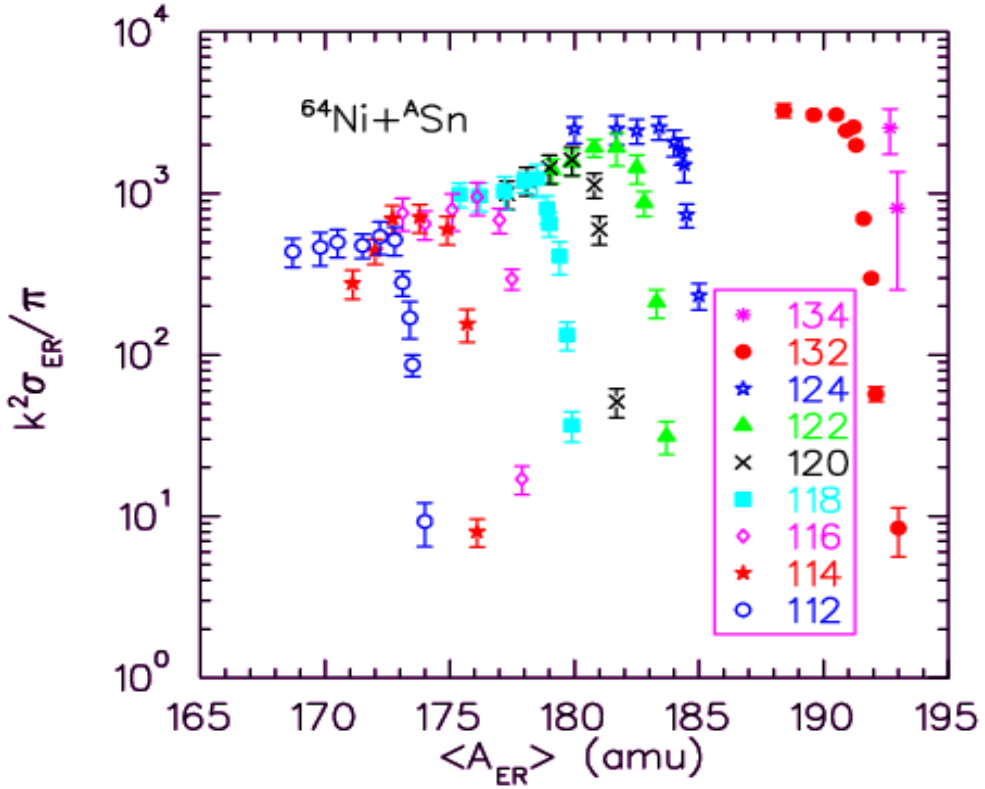
Systematics of ER Cross Section

$$\sigma_{ER} = \frac{\pi\hbar^2}{2\mu E}\Sigma(2l+1)\sigma_l, \quad l=0, l_{ER}$$



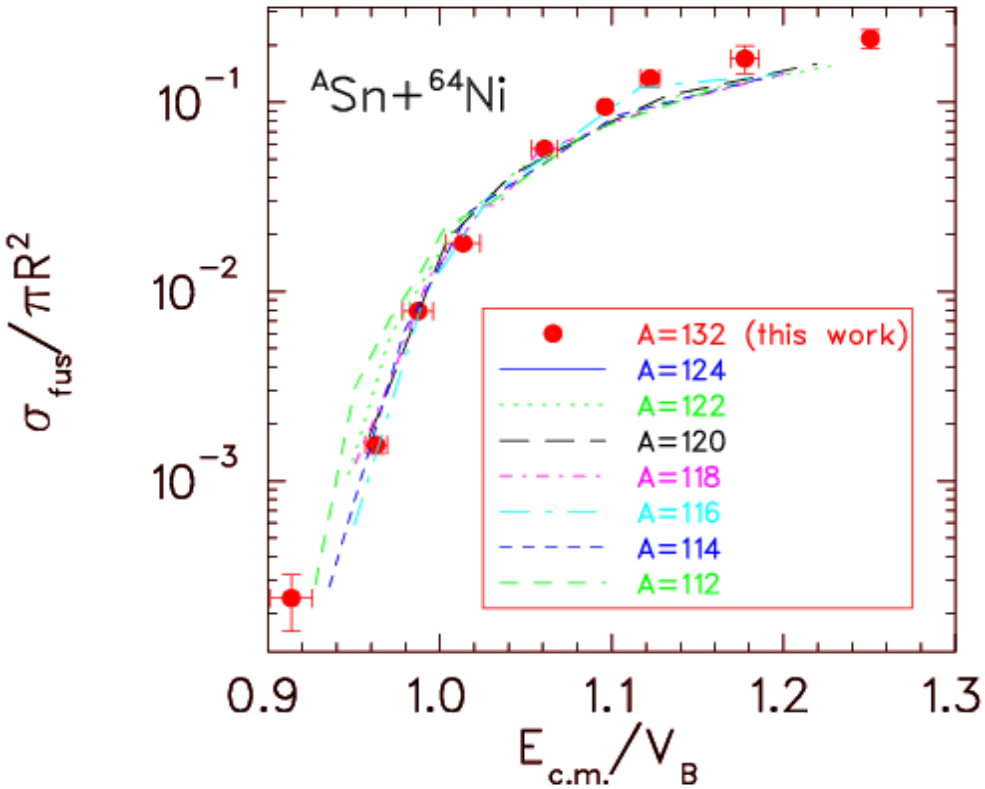
- Factor out $\pi\hbar^2/2\mu E$ for comparison among all Sn isotopes.
- The reduced ER cross section increases as the neutron excess in Sn increases which is consistent with a lower fission probability of the compound nucleus.

Systematics of ER Cross Section



- The average mass of ER, $\langle A_{ER}\rangle$, is calculated by PACE2.
- For A(Sn)>120, the compound nucleus, Pt, decays essentially by neutron evaporation.
- The cross section, for a specific mass of Pt as the final product, is larger when a more neutron-rich Sn is used.
- ERs made with ^{132}Sn cannot be made with stable Sn.

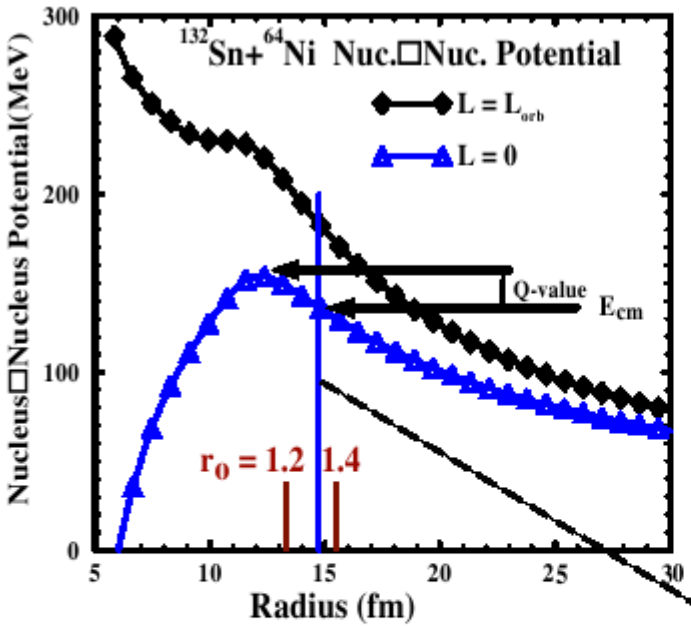
Reduced Fusion Cross Section



- $R=1.2(A_p^{1/3}+A_t^{1/3})$ and V_B=Bass barrier
- No extra fusion enhancement is observed in $^{132}Sn+^{64}Ni$ with respect to other Sn isotopes.

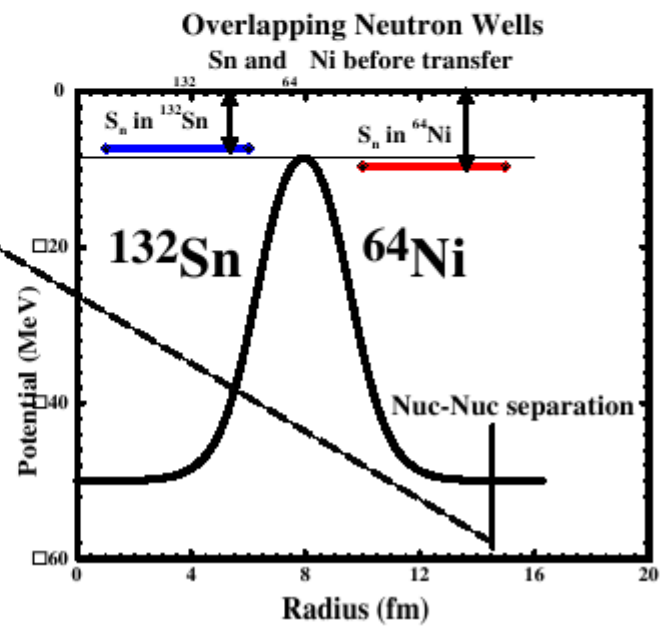
A Prediction Tool - Two-Step Fusion

The intensity of radioactive beam is low.
Need theoretical predictions to help choosing experiments that have large enhancement owing to neutron excess



n-Transfer channels with Q>0.

(~2000) Y. Denisov
V. Zagrebaev



Neutron Flow

P. Stelson
N. Rowley (~1990)

Semiclassical Model

Fusion Cross Section: $$\sigma(E) = \frac{\pi\ \hbar^2}{2\ m\ E} \sum_{l=0}^{Lmax} (2l+1) T_l(E)$$

Transmission coefficient T(E,l) is given as:

$$T(E,l) = \int dB\ f(B) *$$

$$\left\{ N_{tr} \left[\Sigma_{k\neq 0} \int_{-E}^{Q_0(k)} dQ\ \alpha_k(E,l,Q)\ P(B,E+Q,l) \right] + P(B,E,l) \right\}$$

With: $$N_{tr} = \left[\Sigma_{k\neq 0} \int dQ \alpha_k(E,l,Q) \right]^{-1}$$

f(B) = Barrier distribution (excitation/deformation)

α_k(E,l,Q) = prob. of successive transfer of k neutrons.

Form Factor

D. Shapira:

NeutronTransfer FF | Kinematic Factor

$$\alpha_k(E,l,Q)=\exp\{-2\kappa[D(E,l)-D_0]\}\cdot N_k\cdot\exp[-C(Q-Q_{opt})^2]$$

$\kappa=\Sigma_i k(e_i)$ where $k(e_i)=(2\mu_n e_i/\hbar^2)^{1/2}$

n-flow radius

$D(E,l)$= distance of closest approach. $D_0= r_0\cdot(A_t^{1/3}+A_p^{1/3})$

$C= R_b\,\mu_{tp}/\kappa\hbar^2(2E_{cm}-V_b)$ μ_{tp}=Reduced mass in entrance channel.

Barrier penetration calculated at $E_{cm}+Q$

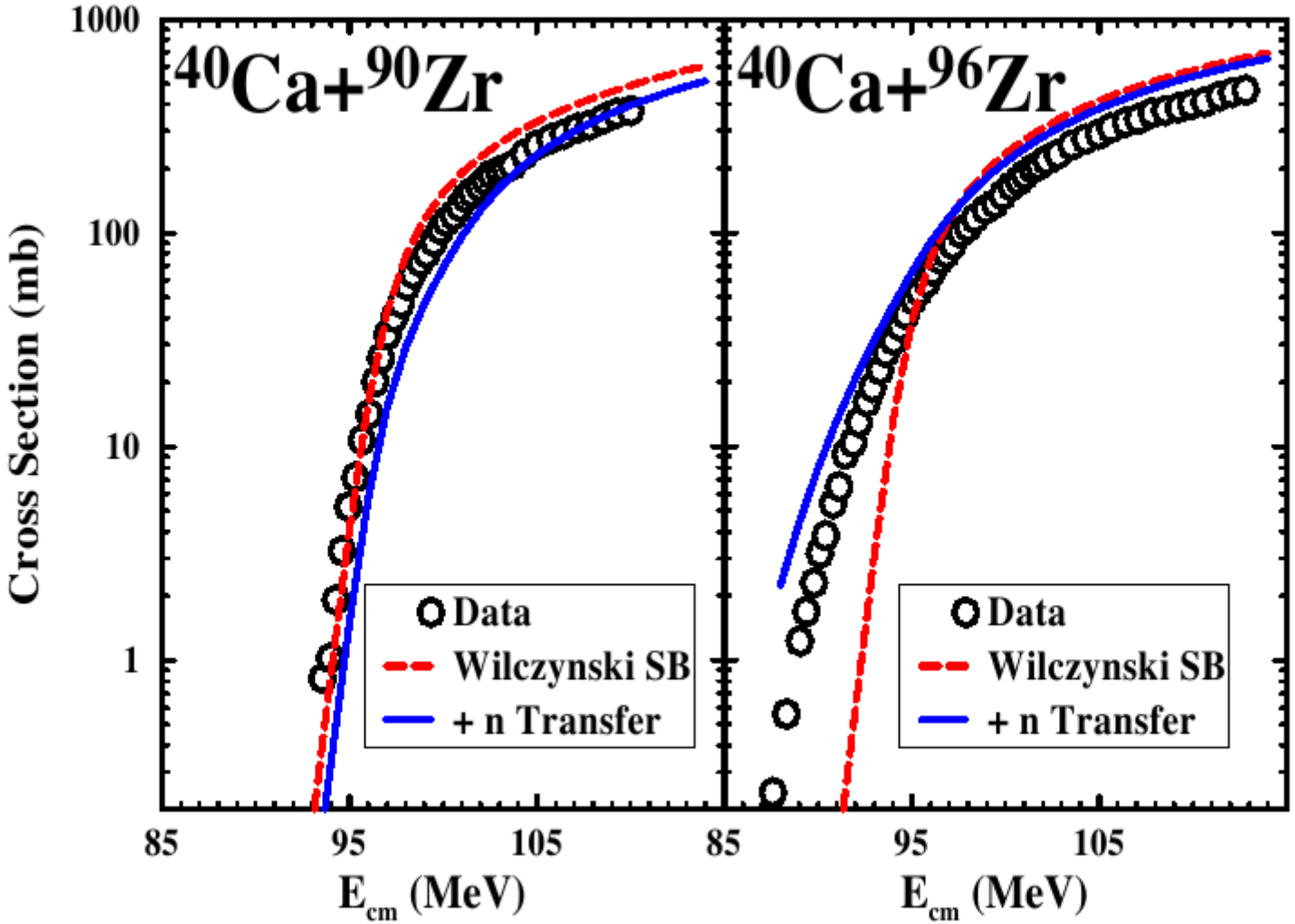
$$P(B,E+Q,l)=\frac{1.0}{1.0+\exp[S_l(E,Q,B)]}$$

$$S_l(E,Q,B)=2\int_{r_1}^{r_2}dr\,\{\frac{2m}{(\hbar c)^2}[V_{nuc}+V_{coul}-(E+Q-B)]+\frac{l(l+1)}{r^2}\}^{1/2}$$

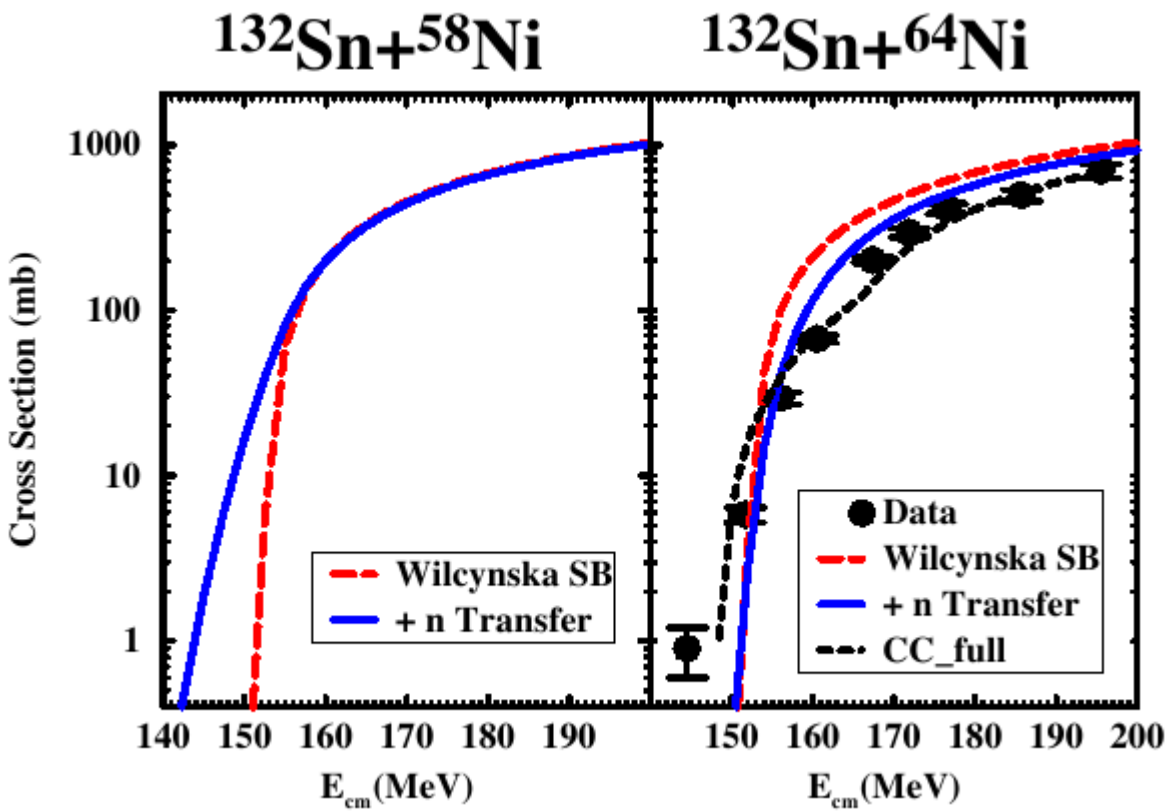
WKB integration

Wilczynski's global potential

A Test Case


^{40}Ca+^{90}Zr
^{40}Ca+^{96}Zr
Cross Section (mb)
1000
100
10
1
85
95
105
E_{cm} (MeV)
Data
Wilczynski SB
+ n Transfer

Predictions



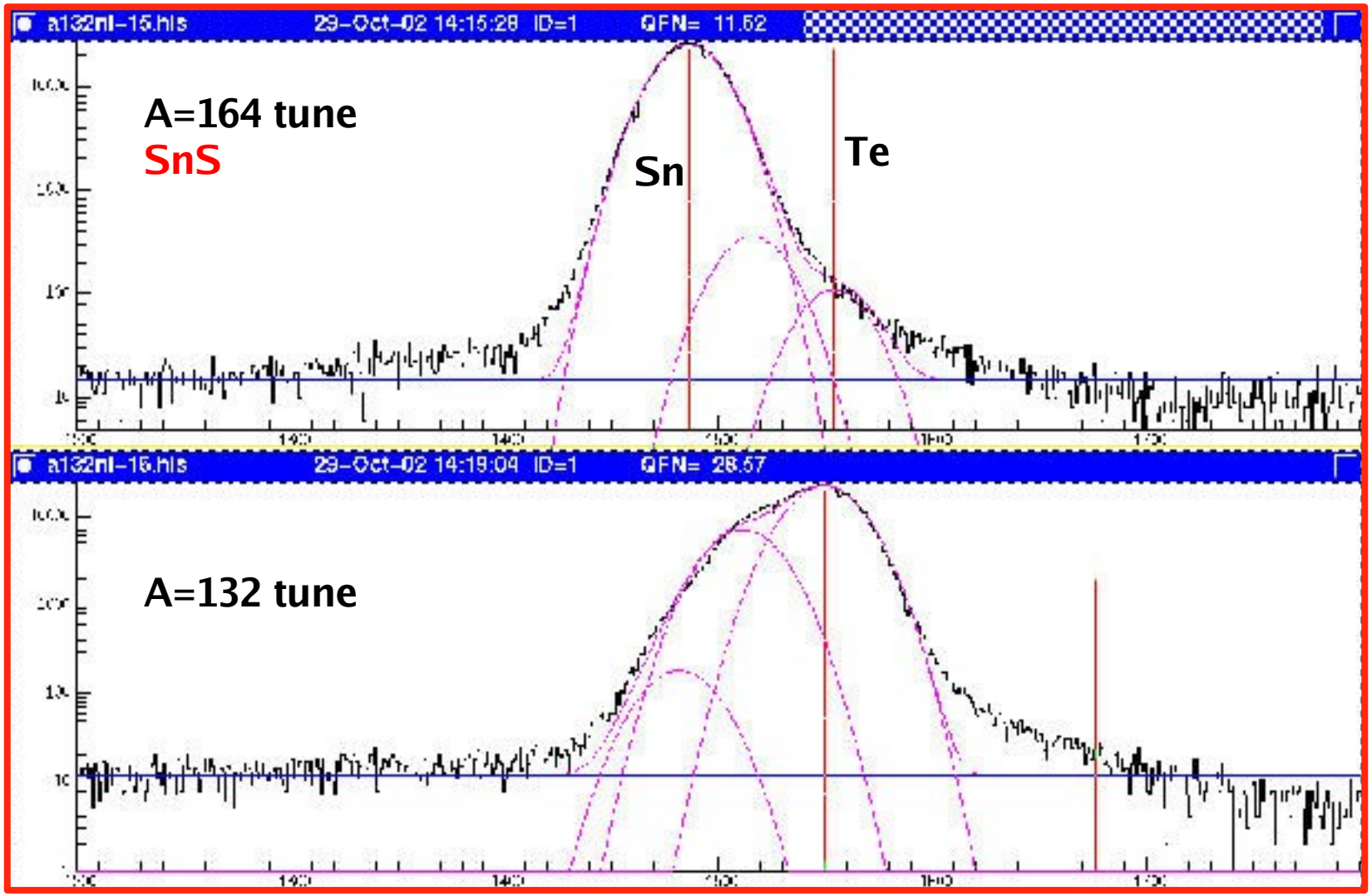
Summary and Outlook

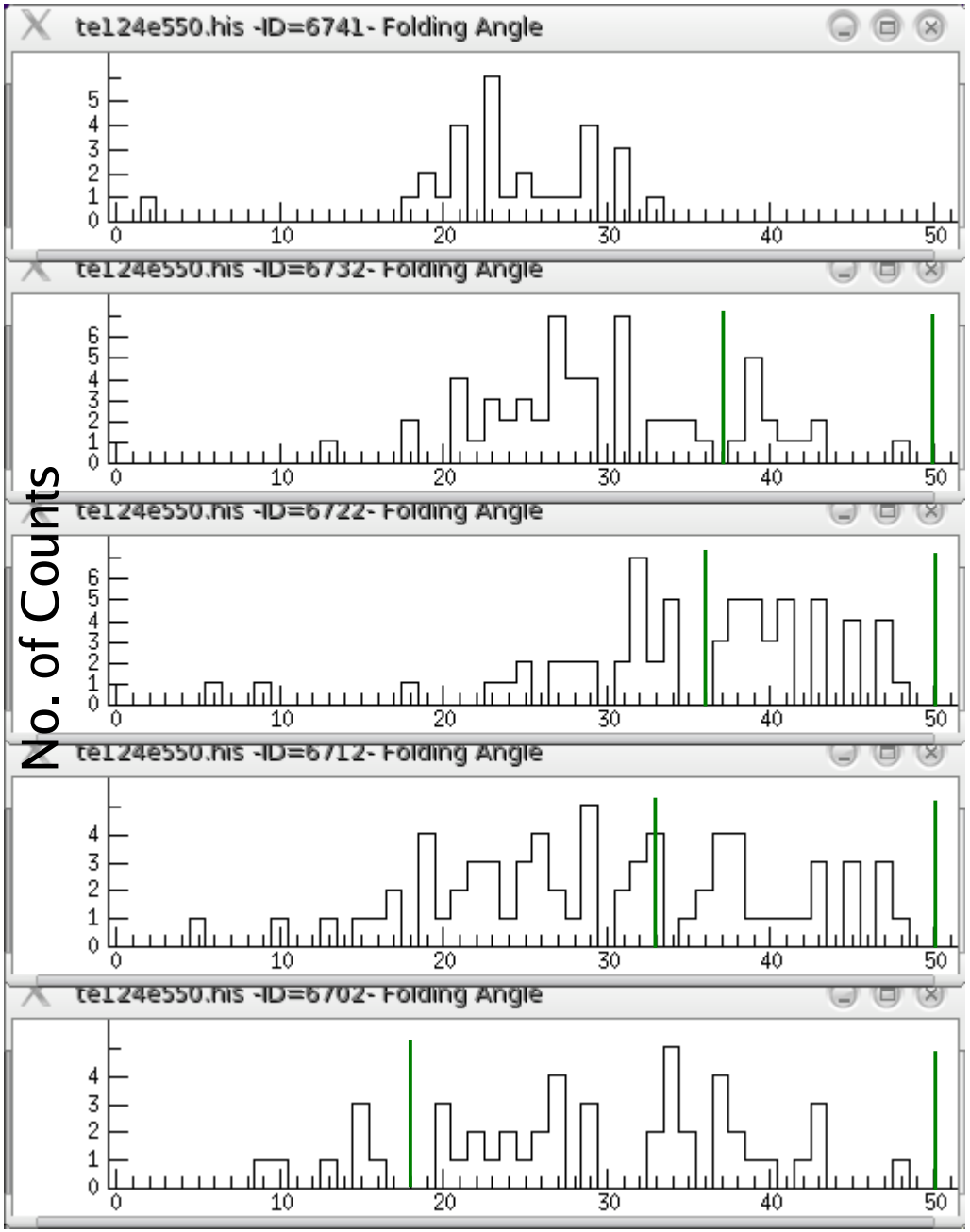
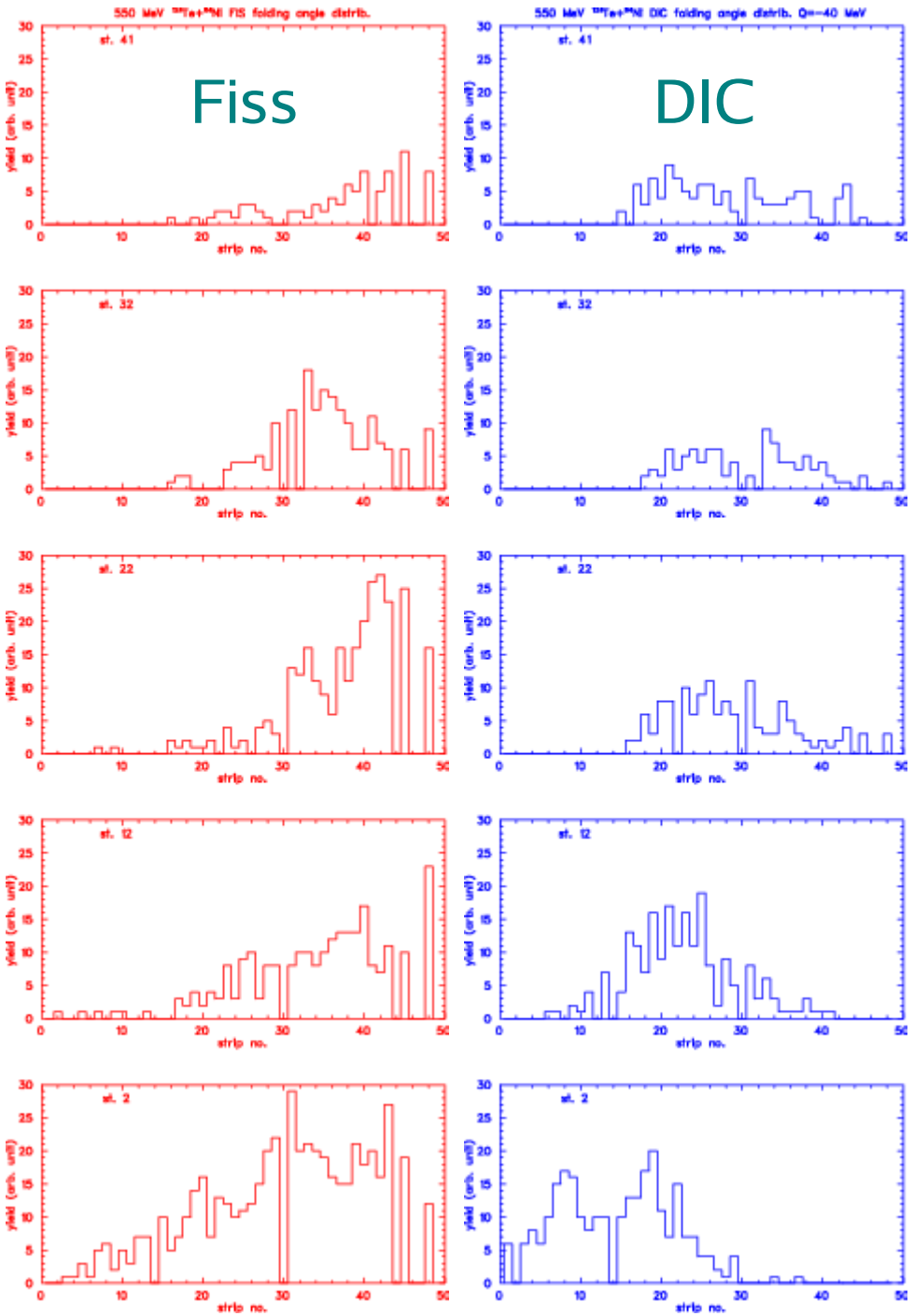
- We have measured ER and fission cross sections for ^{132}Sn on ^{64}Ni.
- The coupled-channel calculation including inelastic excitation and transfer agrees with our data well.
- The fusion enhancement in ^{132}Sn and ^{64}Ni compared to other Sn isotopes can be accounted for by the larger nuclear size of ^{132}Sn.
- We will continue the measurement with ^{134}Sn.
- In the near future, measurements will explore the influence of transfer in ^{132}Sn+^{58}Ni and the entrance channel effects on fusion by comparing fusion of ^{132}Sn+^{58}Ni, ^{126}Sn+^{64}Ni, and ^{30}Si+^{160}Gd.
- Designing a new detector to increase the detection efficiency and improve particle identification.
- Theory on coupling transfer channels

Collaborators

D Shapira, CJ Gross, RL Varner, JR Beene,
A Galindo-Uribarri, J Gomez del Campo, PA Hausladen,
PE Mueller, DC Radford, DW Stracener – ORNL
H Amro, JJ Kolata – University of Notre Dame
JD Bierman – Gonzaga University
AL Caraley – SUNY at Oswego
KL Jones – Rutgers University
Y Larochelle – University of Tennessee
W Loveland, D Peterson – Oregon State University

Beam Impurities



Impurities (no more than 4%) are on the high Z side where higher Coulomb barriers suppress fusion.

Folding angle distributions