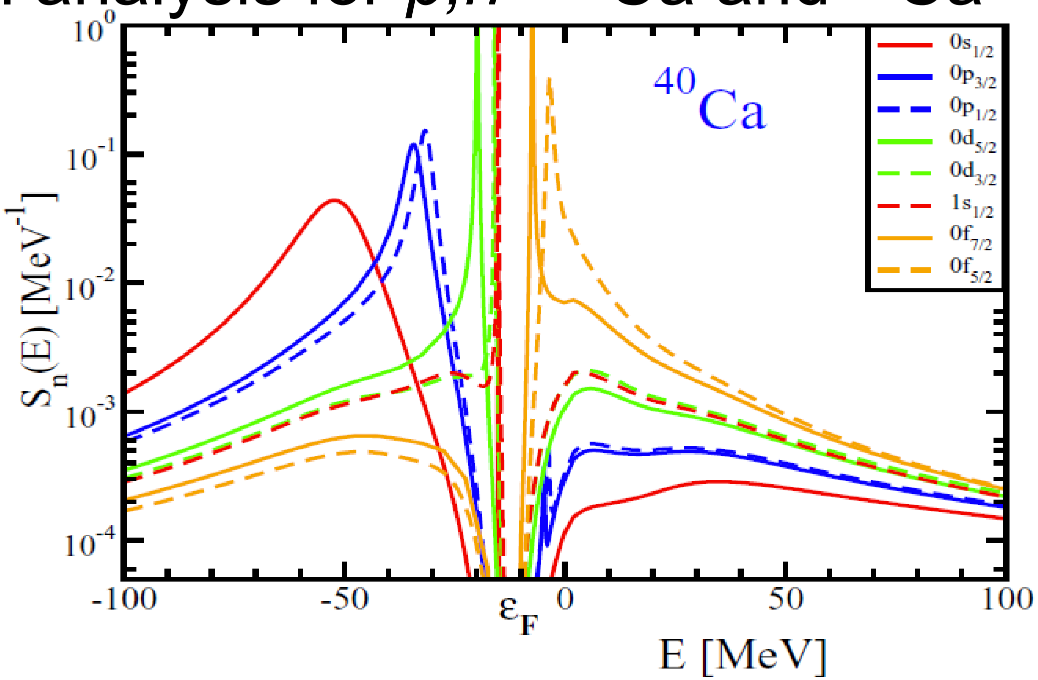
1) Data Needs for Dispersive Optical Model analysis
2) Continuum Spectroscopy of Light Nuclei

Robert Charity
Washington University in St. Louis

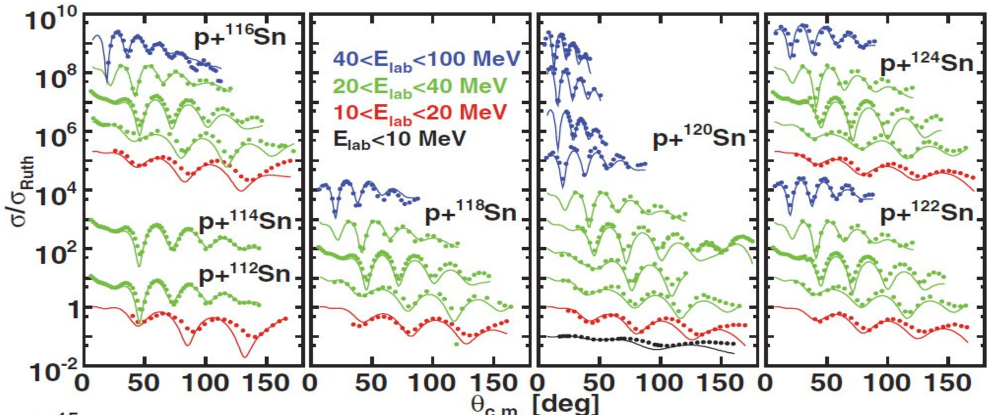
Dispersive optical model

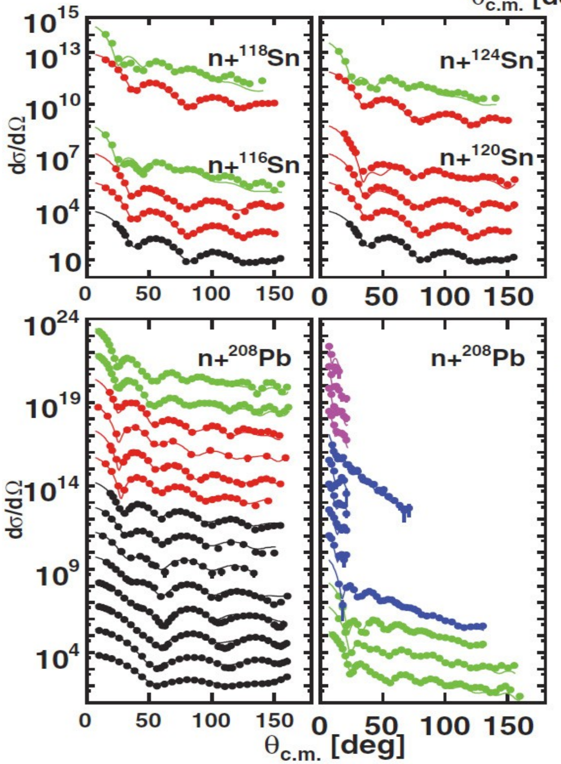
- We have a full non-local analysis for *p,n*+ ^{40}Ca and ^{48}Ca (Hossein Mahzoon)

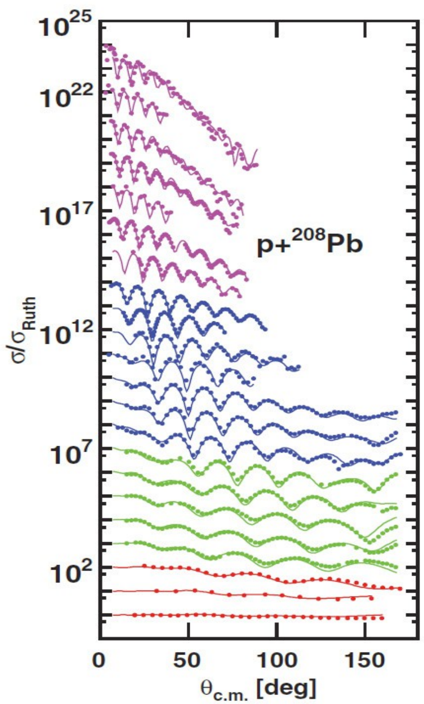


- Local analysis for some of the stable Sn isotopes and ^{208}Pb and other closed-shell systems.
- We would like to like to extend these studies to look at evolution of the structure along an isotope chain from proton drip to neutron drip line.

Examples of data used in local DOM fits
Mueller et al PRC 893, 0464605 (2011)

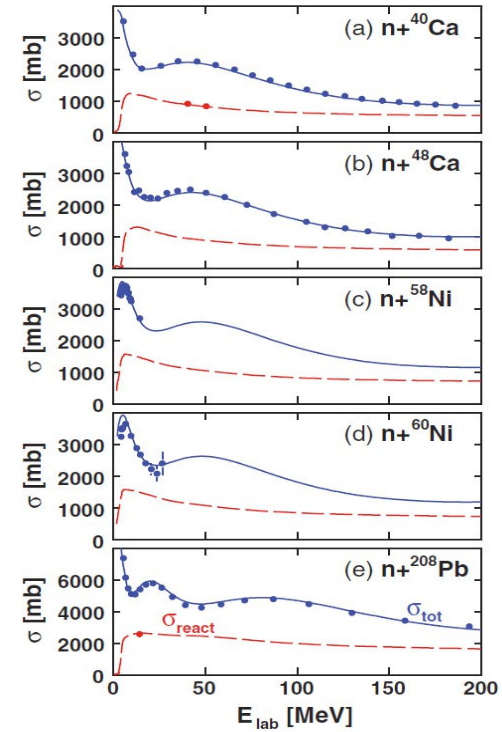


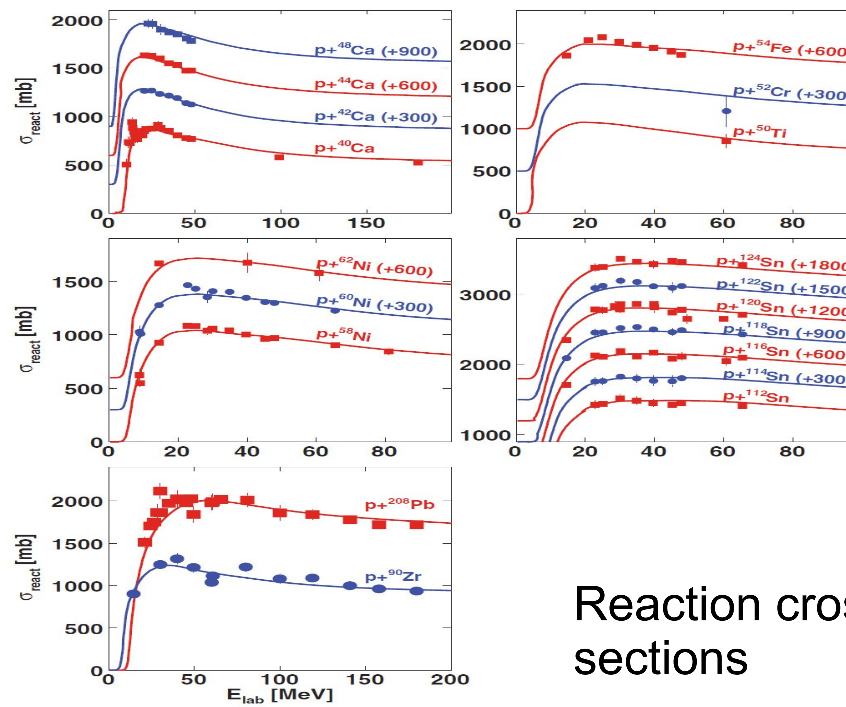




Angular distributions

Total cross sections





Reaction cross sections

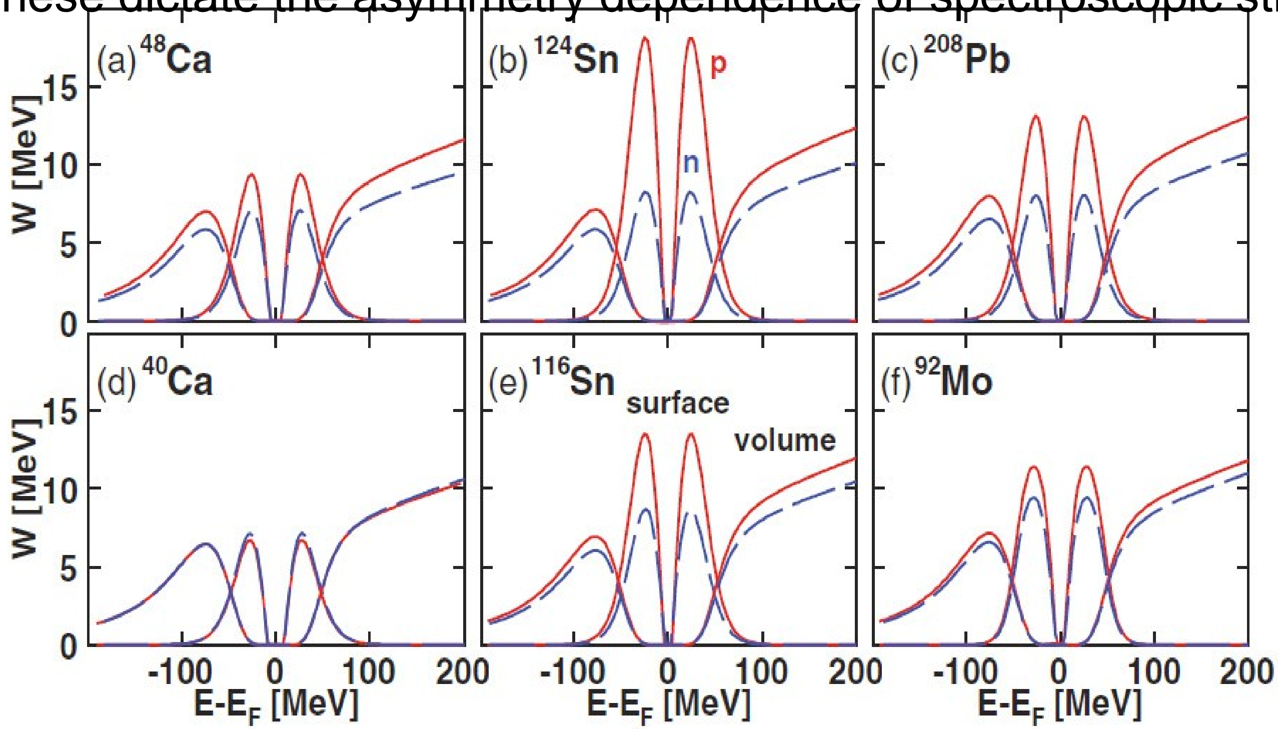
Optical-model potential or nucleon self energy based on the original formalism of Mahaux and Sartor Adv. Nucl. Phys. **20** (1991) 1

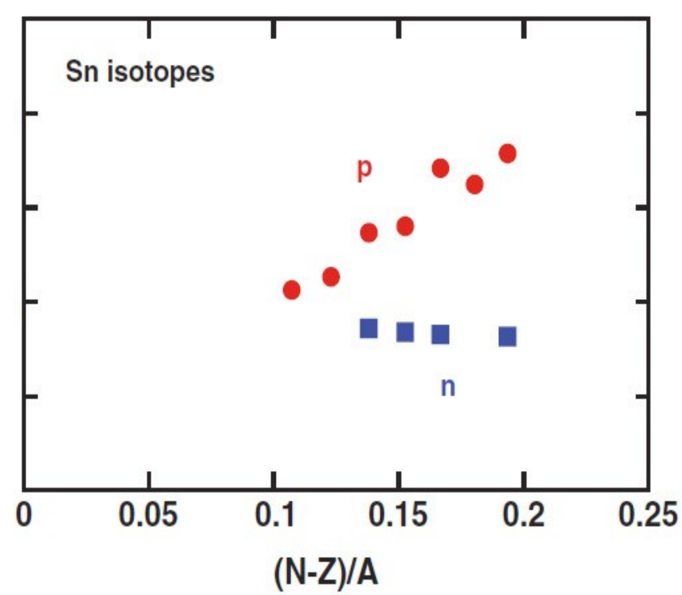
$$\Sigma(r,E)=V_{Coul}(r)+V_{so}(r)+V_{HF}(r,E)+\frac{1}{\pi}\mathrm{P}\int\left(W_{sur}(r,E')+W_{vol}(r,E')\right)\left(\frac{1}{E'-E}-\frac{1}{E'-E_F}\right)dE'$$
$$-i\,W_{sur}(r,E)-i\,W_{vol}(r,E)$$

from $\Sigma(r,r',E)$ one can solve the Dyson equation and get the single-particle propergator $G_{lj}(r,r',E)$

Spectroscopic Strength $S_{j,l}(r,E)=\mathrm{Im}\,G_{j,l}(r,r,E)$

We are very interested in the asymmetry dependence of the imaginary potentials as These dictate the asymmetry dependence of spectroscopic strength, spectroscopic factors, ..





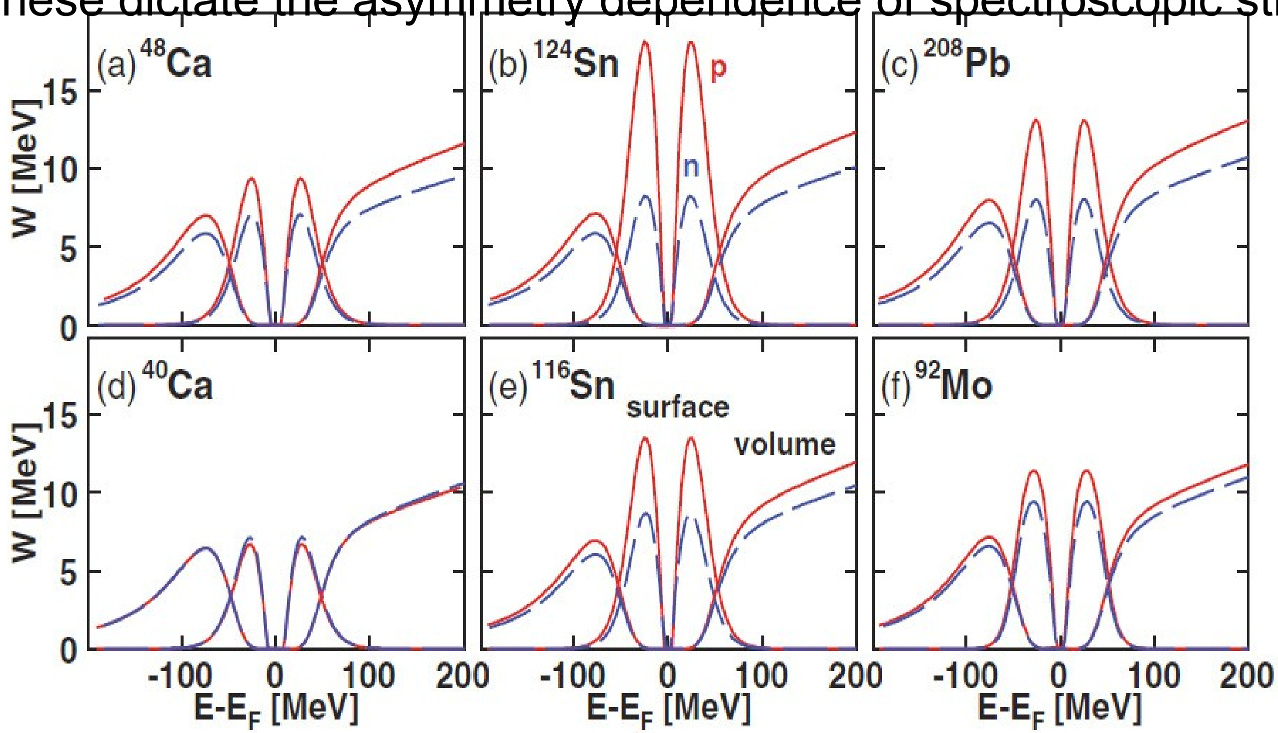
Optical-model potential or nucleon self energy based on the original formalism of Mahaux and Sartor Adv. Nucl. Phys. **20** (1991) 1

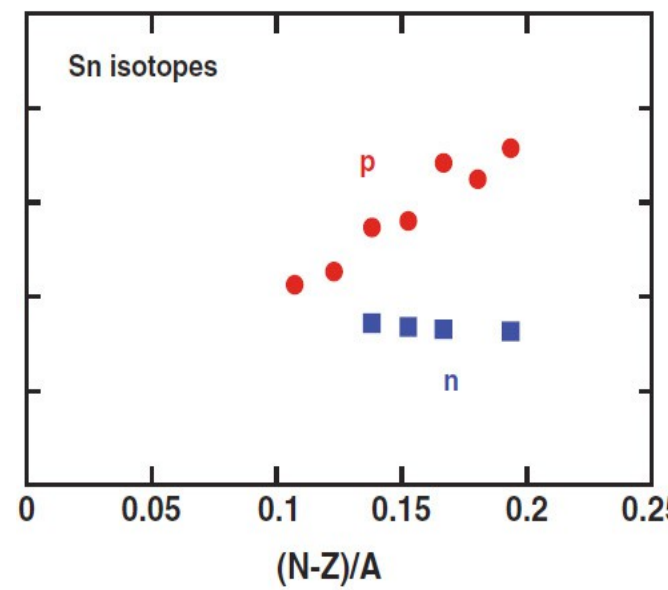
$$\Sigma(r,E)=V_{Coul}(r)+V_{so}(r)+V_{HF}(r,E)+\frac{1}{\pi}\mathrm{P}\int\left(W_{sur}(r,E')+W_{vol}(r,E')\right)\left(\frac{1}{E'-E}-\frac{1}{E'-E_F}\right)dE'$$
$$-iW_{sur}(r,E)-iW_{vol}(r,E)$$

from $\Sigma(r,r',E)$ one can solve the Dyson equation and get the single-particle propergator $G_{lj}(r,r',E)$

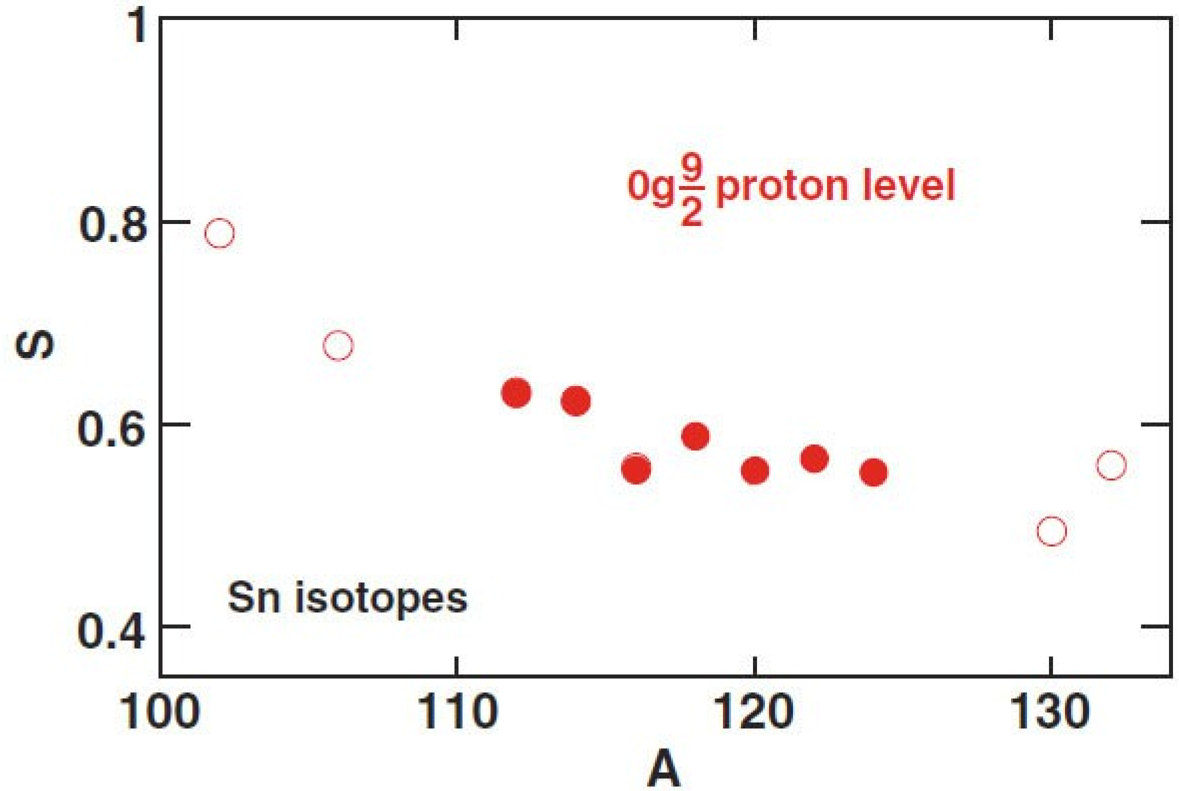
Spectroscopic Strength $S_{j,l}(r,E)=\mathrm{Im}\,G_{j,l}(r,r,E)$

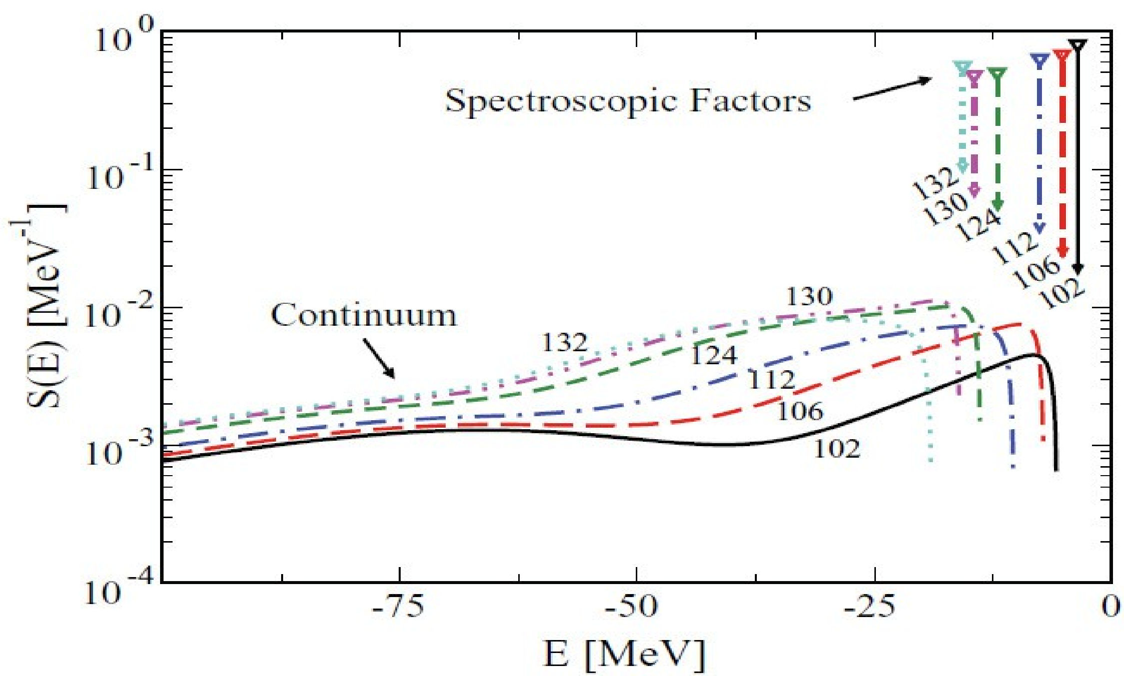
We are very interested in the asymmetry dependence of the imaginary potentials as These dictate the asymmetry dependence of spectroscopic strength, spectroscopic factors, ..





Asymmetry dependence of $g_{9/2}$ proton levels in Sn Isotopes





Protons

- Already lots of data available on stable separated isotopes. Further work could be contemplated, easy experimentally. Proton beam and detector with good resolution. Target chemistry maybe the most difficult part.
- The most interesting challenge is to extend these studies to unstable isotopes using inverse kinematics with hydrogen or polyethylene targets. Detect elastically scattered proton in coincidence with beam particle.
- Problems

  a) use of thick-targets and/or secondary beams decreases energy resolution of experiment. Makes it difficult to separate elastic from inelastic scattering. Choose closed-shell nuclei where first-excited state is well separated from ground state.

  this problem may go away at drip lines if excited states particle decay.

  e.g. ^{36}Ca ?

- c) Large range of proton energies, from 0 to twice beam E/A
- d) Need large solid angle coverage due to low beam intensities.

Protons

- Most useful energy regime 10 < E/A < 30 MeV

  E/A < 10 discreet resonances;

  E/A > 50 volume absorption dominates, smaller asymmetry dependence

  surface absorption peaks at ~20 MeV/A

  Not well suited to most radioactive beam facilities.

- FRIB not well suited for this.

  400 MeV/A secondary fragmentation beams

  <10 MeV/A reaccelerated beams (ReA10)

  Can do ~15 MeV/A ^{36}Ca

- TEXAS A&M Mars separator 10-30 MeV/A. Not very exotic compared to FRIB. We plan to do ^{14}O (E^*_1=5.17 MeV) and ^{20}O (E^*_1=1.67 MeV) this year. Already lots of ^{16}O and ^{18}O data. Δ(N-Z)/A = 0.4 (greater than that ^{40,48}Ca)

- No N<Z data exits right now.

- Will it be possible to do ^{132}Sn and ~^{106}Sn? (URISOL)

Neutrons

- Neutron scattering on radioactive beams is not possible, but there is very little neutron scattering on separated isotopes.
- Main problem is cost. Neutrons have small interaction cross sections, need substantial amount of separated isotope.
- e.g. ^{48}Ca we used 2.7 grams $300000.00

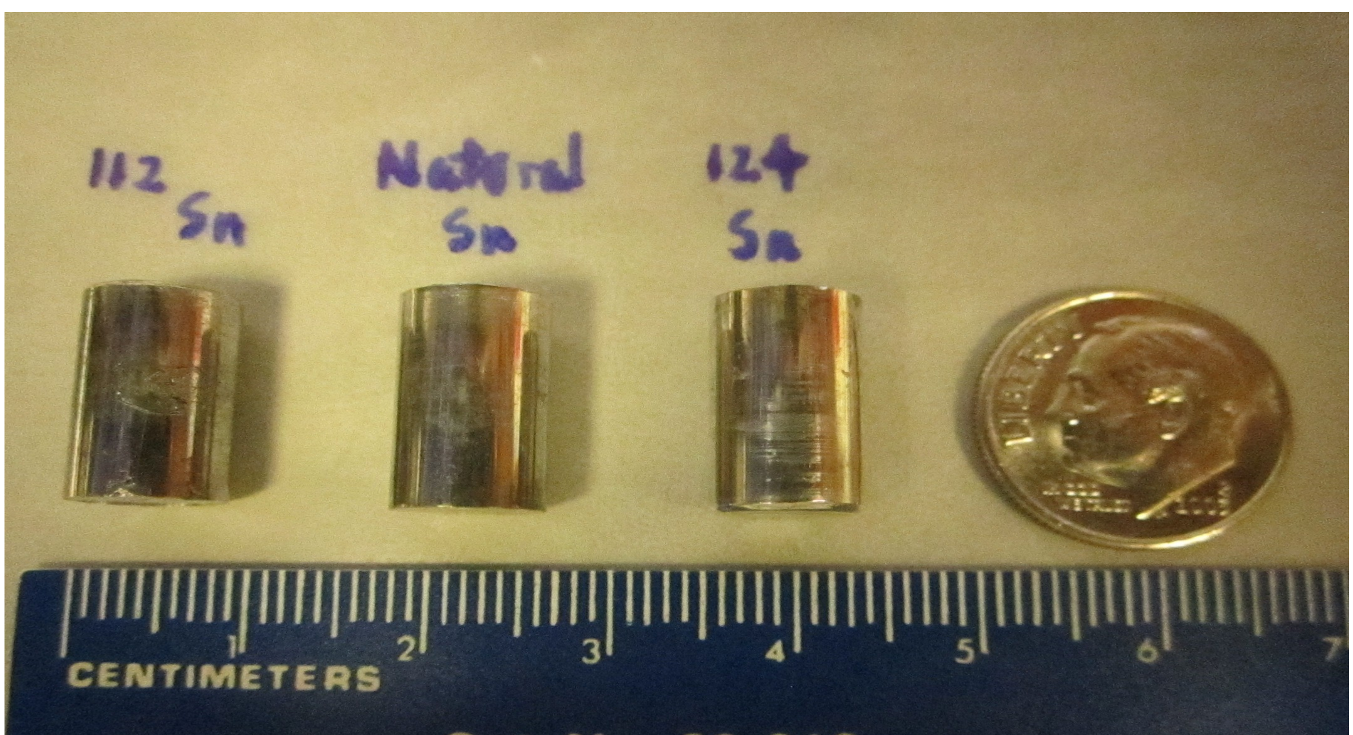
  Material was borrowed from NSCL (used in ion source for beam production)

  TUNL - elastic-scattering angular distributions (11.9, 16.9 MeV)

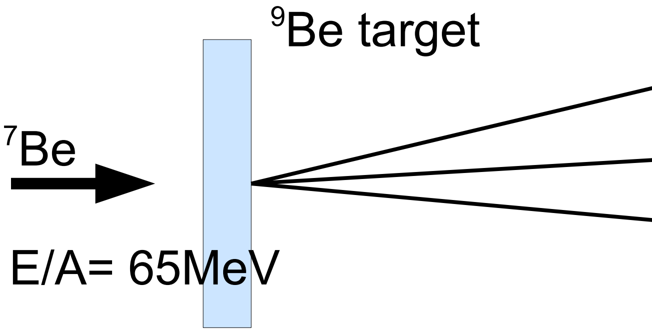
  LANSCE – total reaction cross sections (15-300 MeV)
- Used in nonlocal analysis of n+^{48}Ca

Neutrons

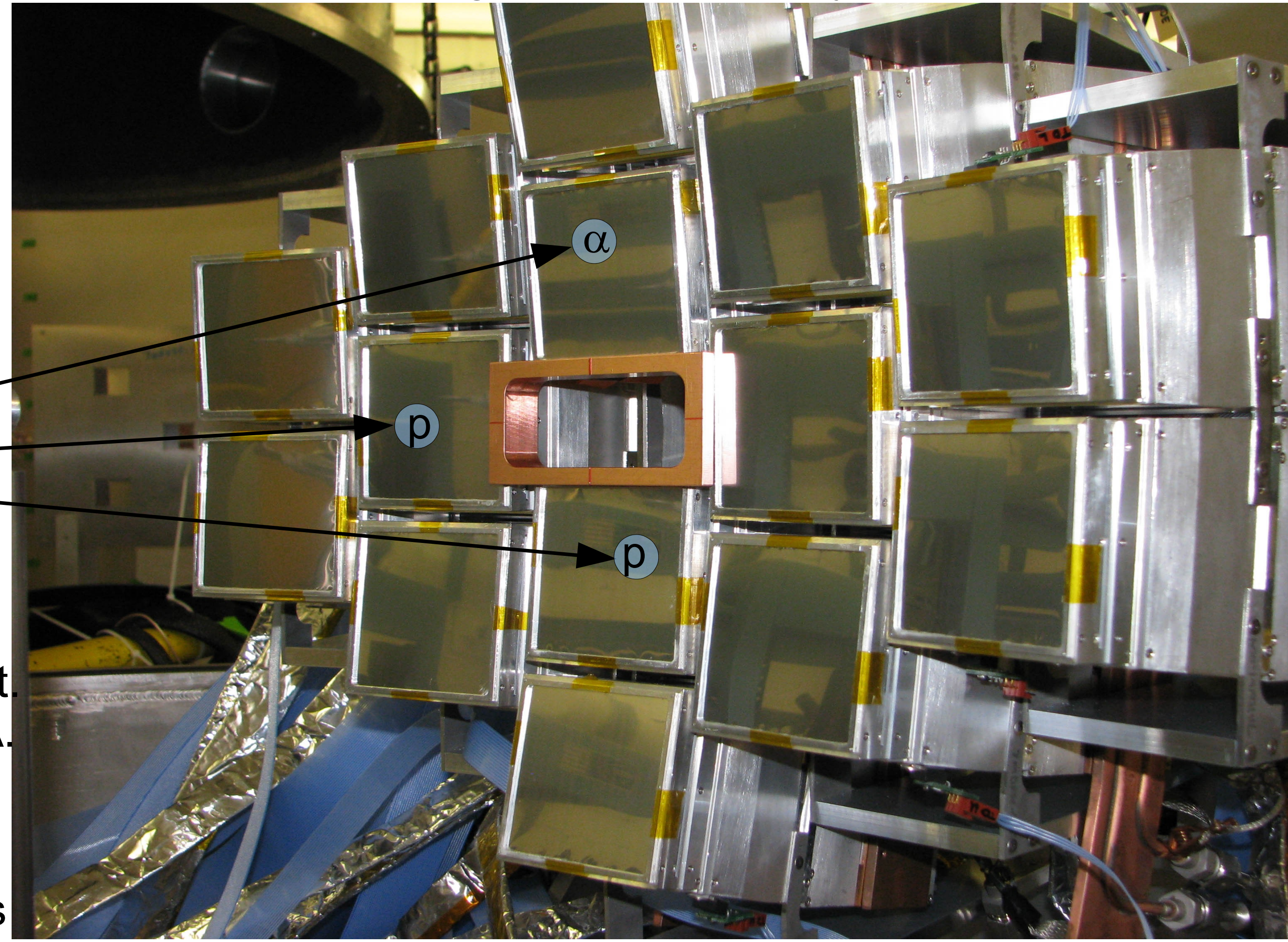
- n+^{116,118,120,124}Sn angular distributions have been measured, but no total cross sections.
- We have acquired ~5 grams of each ^{112}Sn and ^{124}Sn, for angular distributions and total cross section measurements at LANSCE and TUNL



HiRA array
Washington University
Michigan State,
Western Michigan
Indiana University
Milan



High Resolution Array.



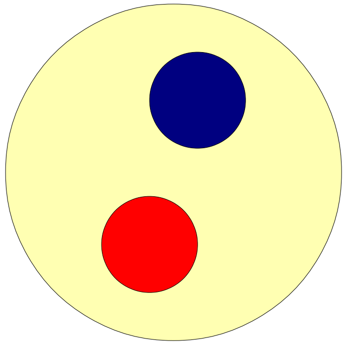
Si-CsI E-ΔE telescopes

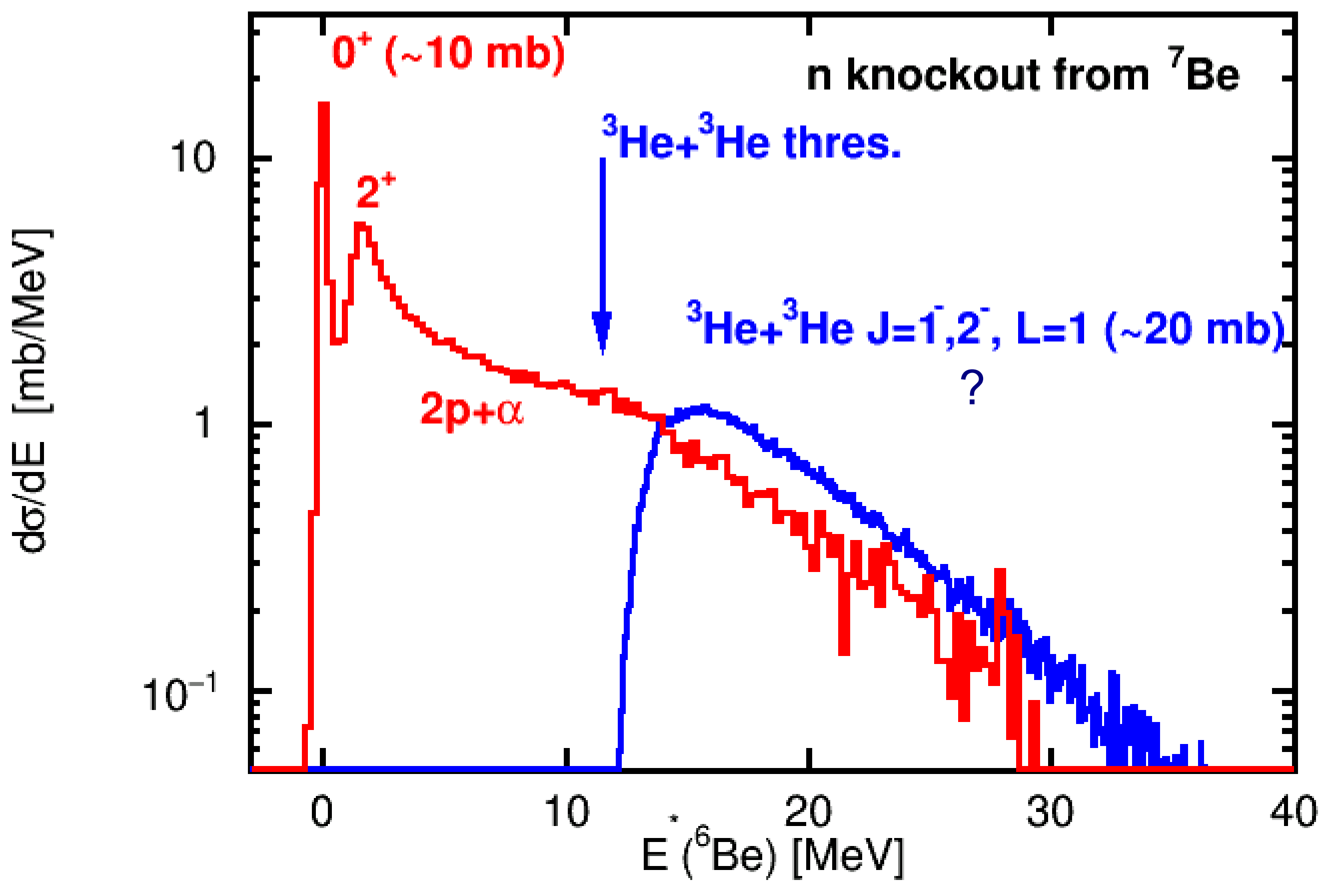
Parent nucleus decays in target.
Detect decay products in HiRA.
Need high angular resolution
(Si Strips)

1.5 mm DSSD has 32x32 strips
~800 Si strips in experiment.
Chip readout.
Multi-hit capability – multiple fragments in a single telescope

Invariant-mass Spectroscopy with HiRA
Investigating the structure of light nuclei

Neutron knockout from ^{7}Be ($J=3/2^{-}$) E/A=65 MeV ^{9}Be target





Knocking a *n* from the ^{3}He, should give up positive parity ^{6}Be states.

Knocking a *n* from the α, should give us negative parity ^{6}Be states

Wide ^{3}He-^{3}He $0^{-},1^{-},2^{-}$ states with total spin =1 and L=1 are predicted near $^{3}He+^{3}He$ threshold.
Thompson and Tsang
NPA 106 591 (1968)
Arai, Kato, Aoyama,
PRC 74 03405 (2006)

Dependence of resonances on structure of initial state

^{7}Be → *n* knockout + ^{6}Be
Grigorenko et al, PRC **86**, 061602(R)
2p+α model hyperspherical coordinates

$$\left(\hat{H}_3 - E_T\right)\psi^{(+)} = \phi_q$$

$\psi^{(+)}$ wave function with pure outgoing asymptotics
ϕ_q source term from ^7Be wavefunction with sudden neutron removal

$$\langle\Psi_{^4\mathrm{He}}|\Psi_{^7\mathrm{Be}}\rangle = \alpha[p_{3/2}[p^2_{3/2}]0]_{3/2} + \beta[p_{3/2}[p^2_{1/2}]0]_{3/2}$$
$$+\gamma[p_{3/2}[p^2_{3/2}]2]_{3/2} + \delta[p_{3/2}[\frac{p_{3/2}p_{1/2} - p_{1/2}p_{3/2}}{\sqrt{2}}]2]_{3/2}. (3)$$

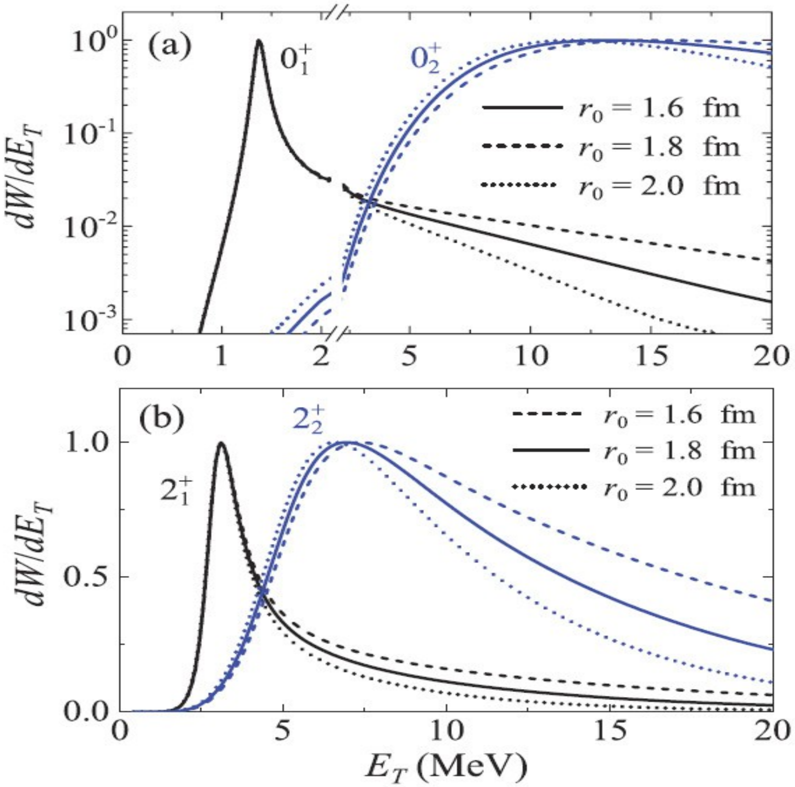
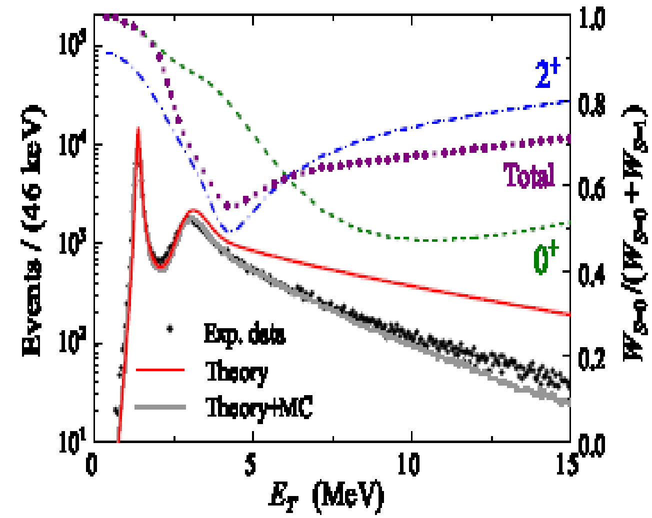


FIG. 5. (Color online) Dependence of the ^{6}Be excitation spectra on the radius parameter r_0 of the ^{7}Be WF. All spectra are normalized to a maximum value of unity.

Narrow resonances: centroid correlations are independent of structure of initial state and reaction Mechanism



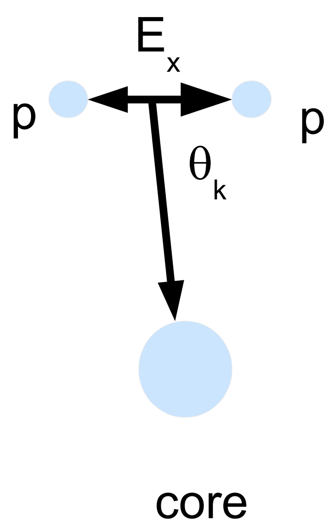
Sensitivity to structure of ^{7}Be

Correlations in 3-body decay.

Can be completely described by a two-dimensional distribution.

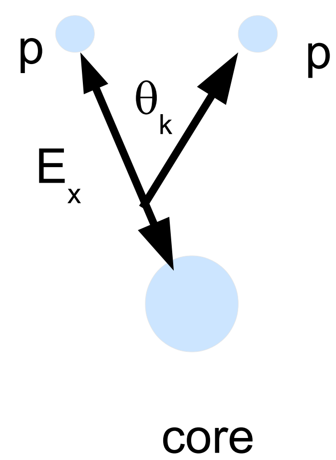
Usually in terms of the Hyperspherical coordinates via energy and angle parameters.

Jacobi T

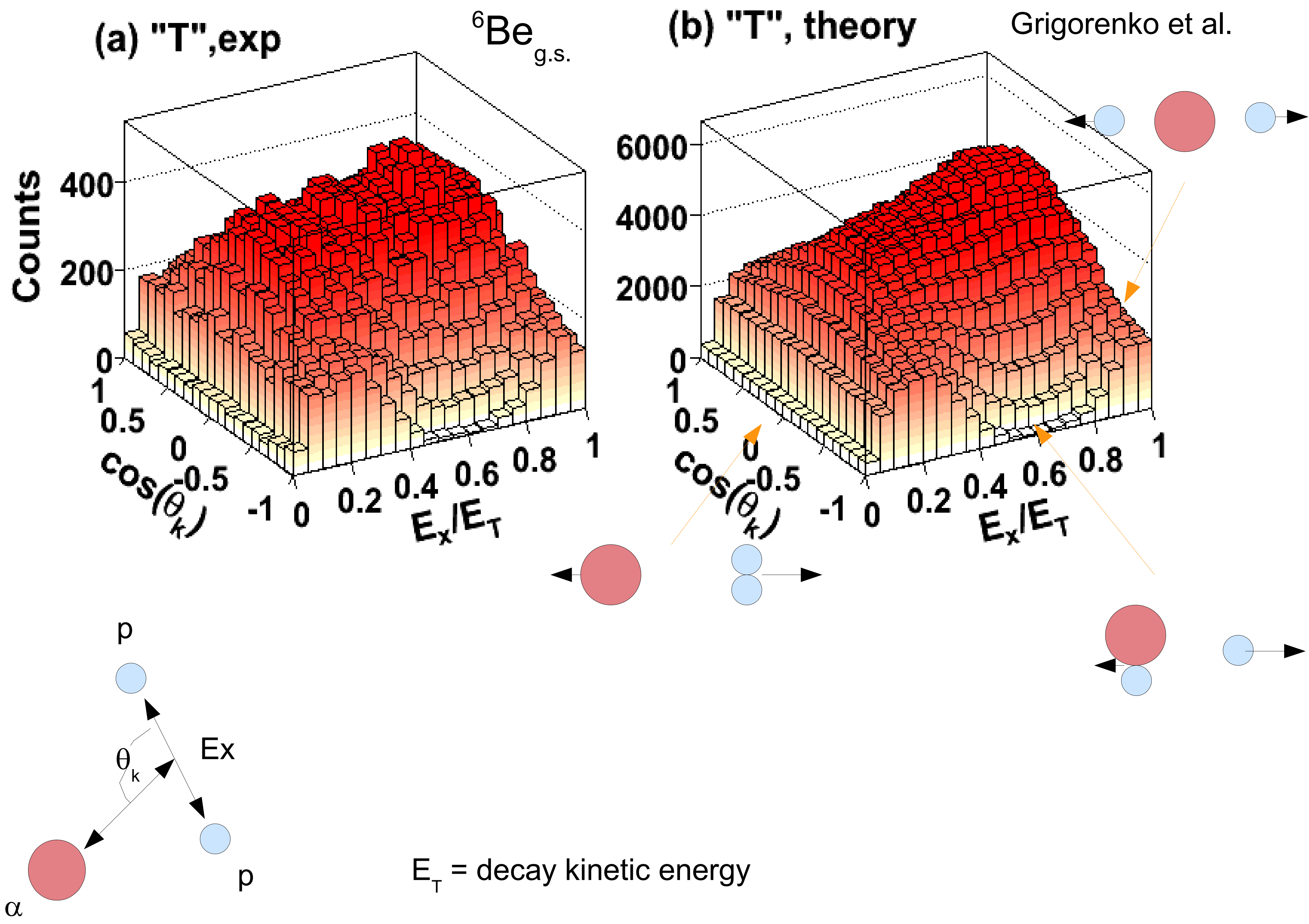


$E_x = E_{p\text{-}p}$

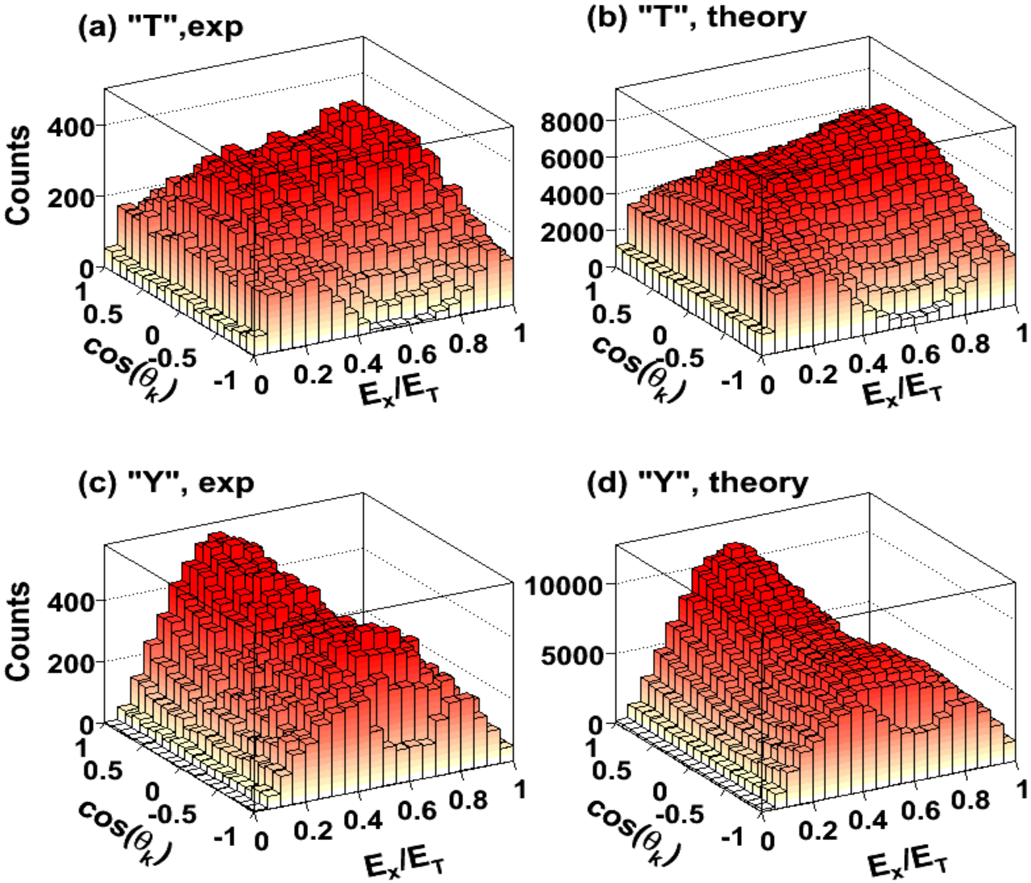
Jacobi Y



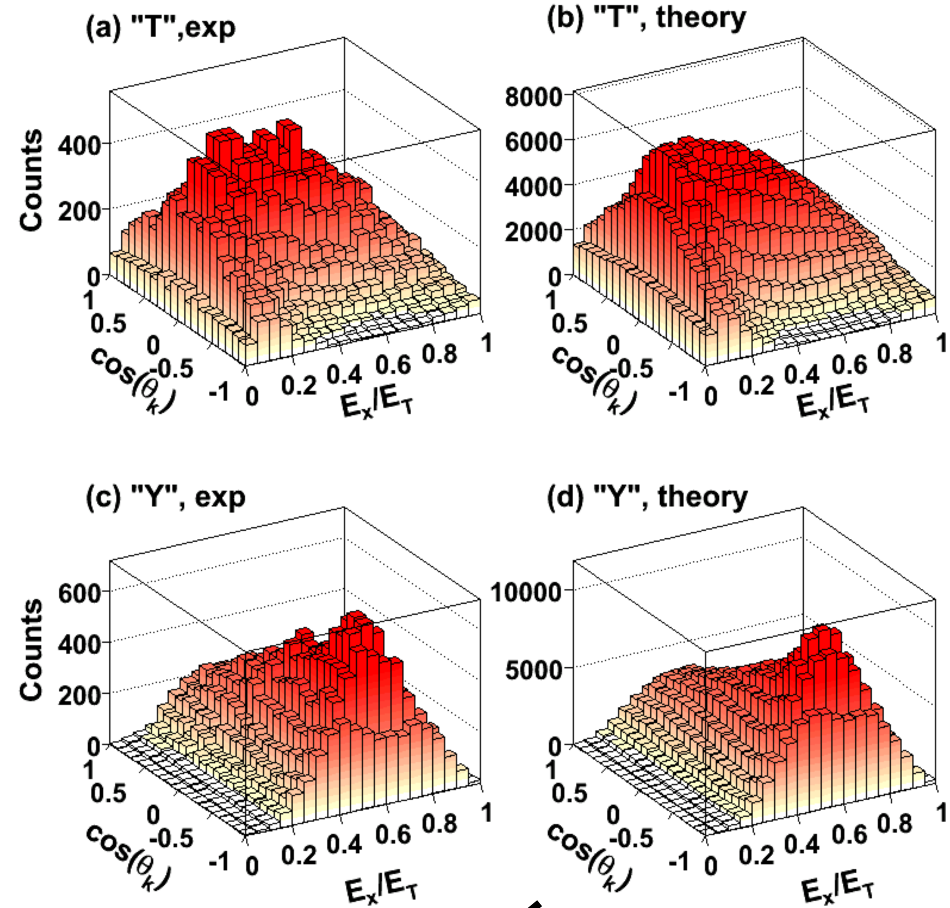
$E_x = E_{p\text{-}core}$



(a) "T",exp
$^{6}Be_{g.s.}$
(b) "T", theory
Grigorenko et al.
Counts
400
200
0
6000
4000
2000
0
1
0.5
0
-0.5
-1
cos(θ_k)
0
0.2
0.4
0.6
0.8
1
E_x/E_T
p
Ex
θ_k
p
α
E_T = decay kinetic energy

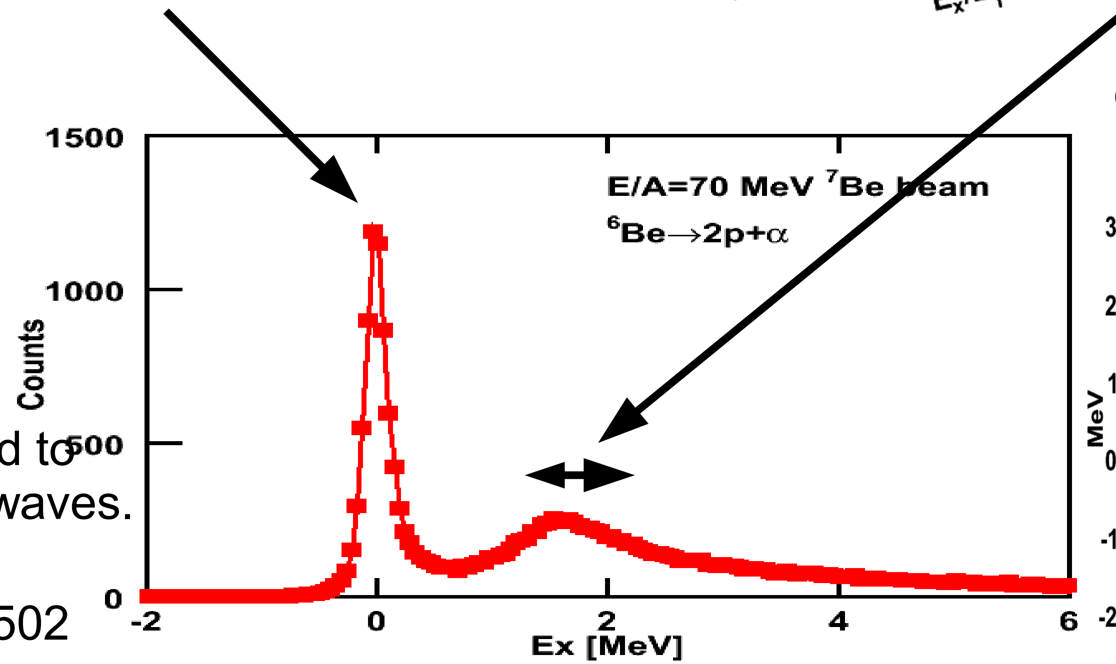


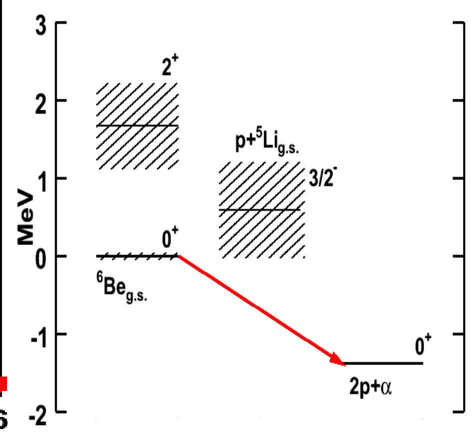
^{6}Be ground-state 0^+



^{6}Be 1st excited stateJ=2^+

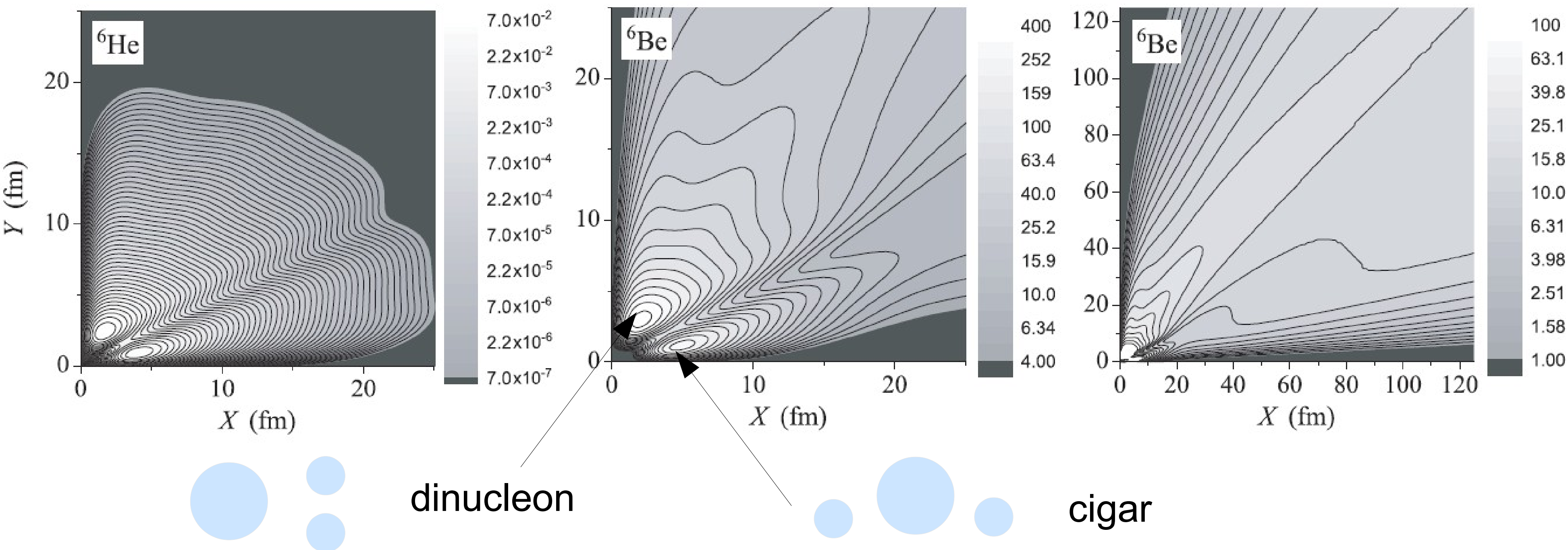
Grigorenko's
3-body cluster model.
2 and 3-body forces.
Wavefunctions matched to
approximate outgoing waves.



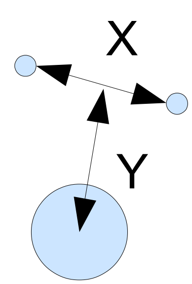


PRL 109 (2012) 202502

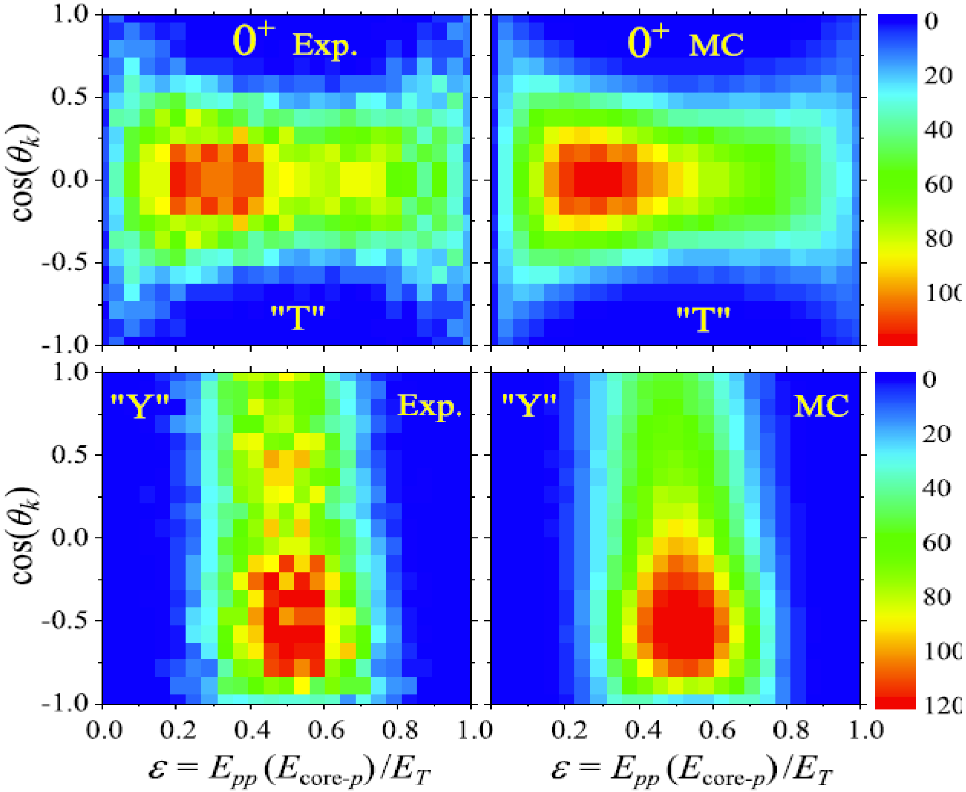
$^{6}Be_{g.s.}$ and $^{6}He_{g.s.}$ wavefunctions

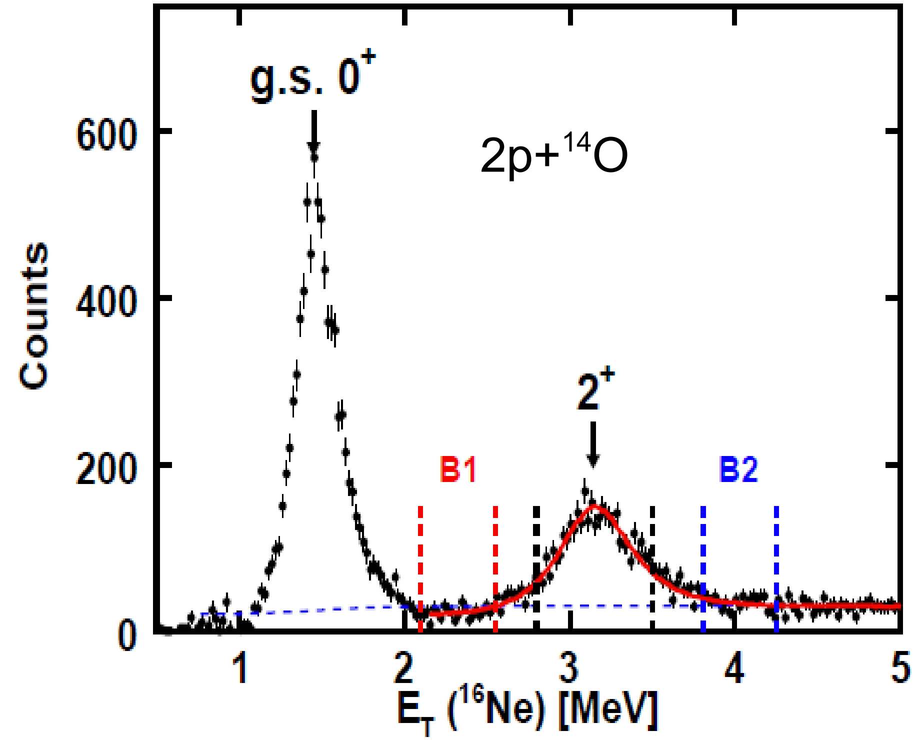


Grigorenko PRC 80 (2009) 034602



^{16}Ne states produced via *n* knockout from a ^{17}Ne beam (E/A = 65 MeV, ^{9}Be target)





Experiment

Theory
(Grigorenko et al)

Brown et al , PRL 113, 232501 (2014)

Ground-state correlations

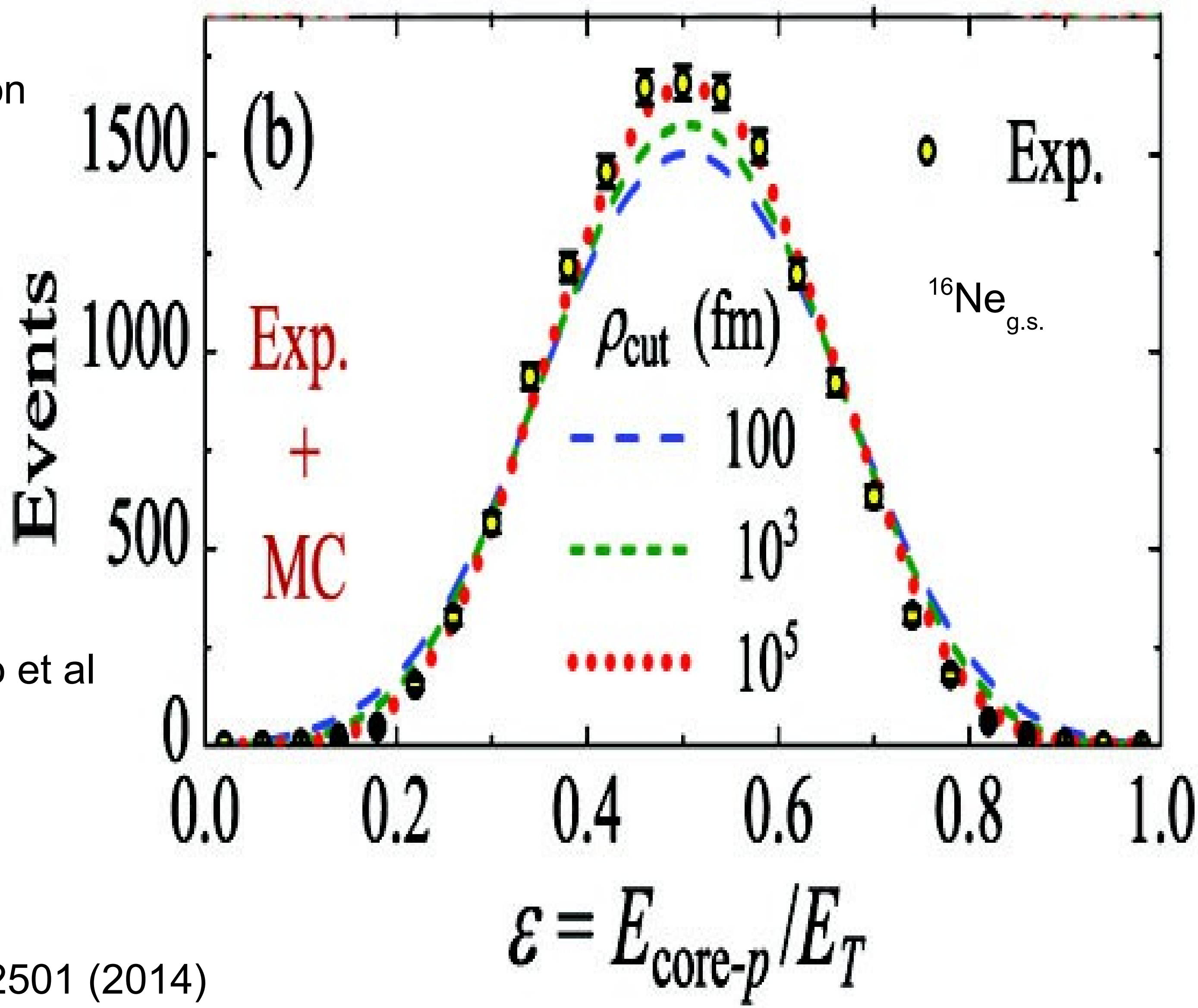
2p decay of ^{16}Ne ground state

Long-range 3-body Coulomb interaction

Three-body Coulomb interaction needs to to considered out to large distances > 100000 fm

Quantal treatment > 200 fm, then Classical extrapolation.

This will become more important for heavier 2*p* emitters



Calculations of Grigorenko et al

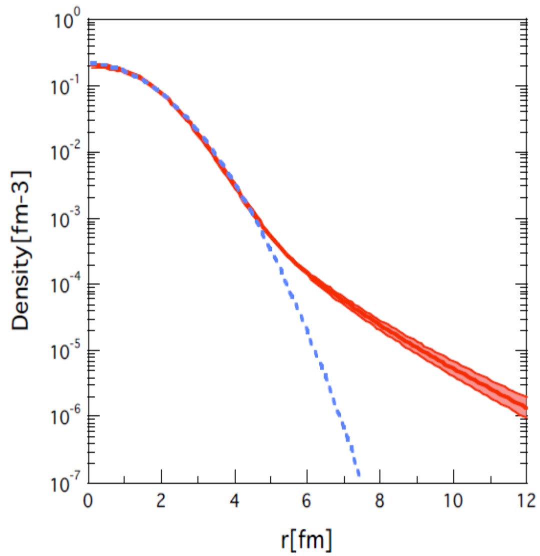
Brown et al , PRL 113, 232501 (2014)

$\rho^2 = X^2 + Y^2$

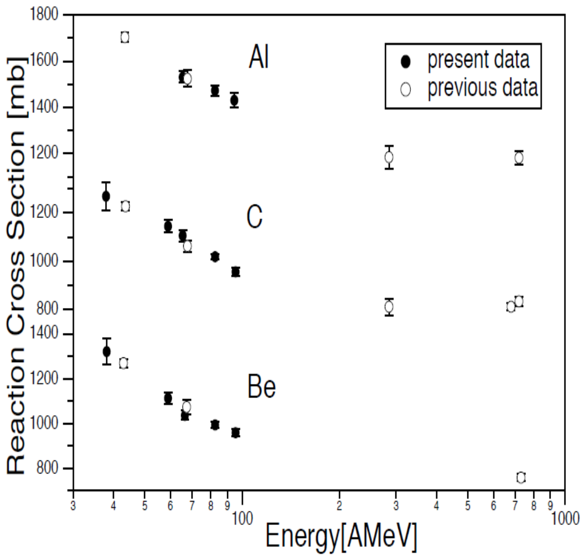
Add two more protons to ^7Be projectile

Neutron Knockout from ^9C (E/A=65 MeV ^9Be target)
Does it still have cluster structure?
Does it have a 2-proton halo? S_{2p} = 1.43 MeV

Furutachi et al Modified AMD
Prog. Theor. Phy. 122 (2009) 122
Mixture of cluster and single-particle structure

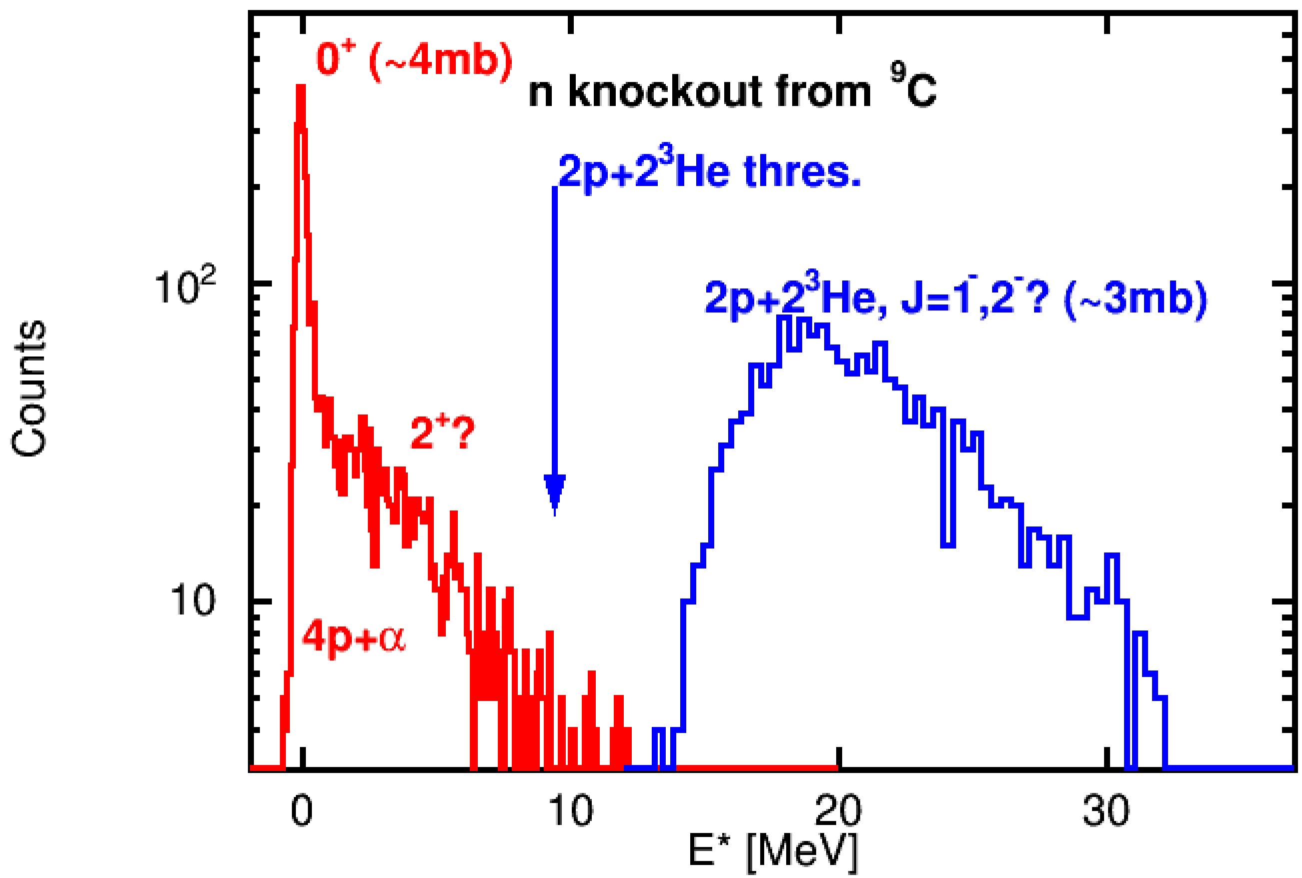


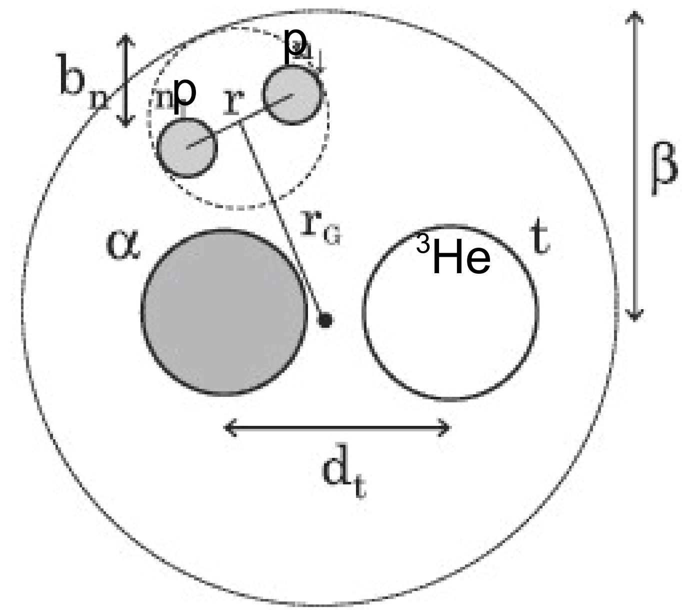
Nishimura et al



E/A=65 MeV ^9C on ^9Be target

Neutron knockout making ^8C resonances



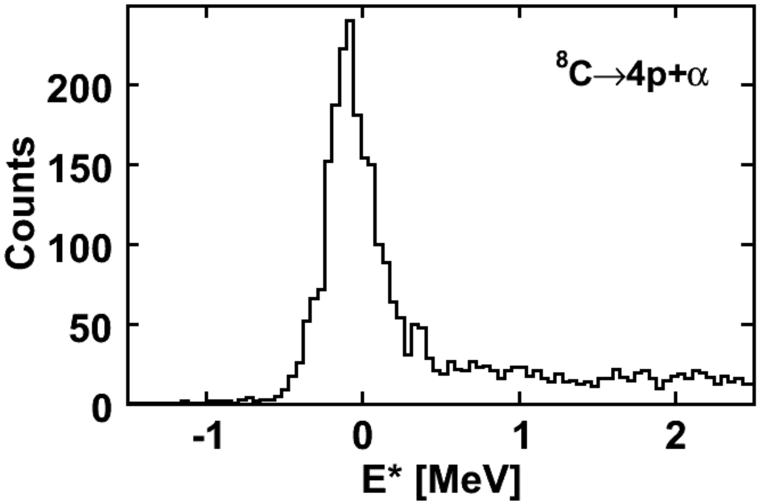


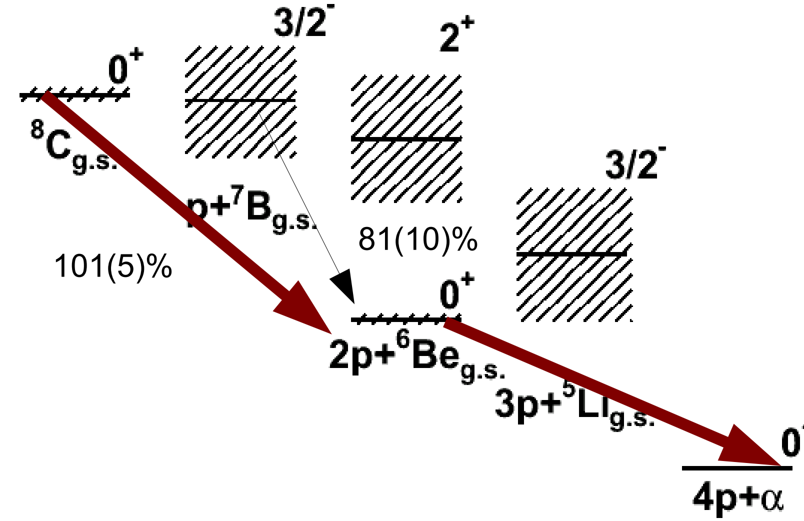
Diproton + α + ^{3}He Structure.
Kobayashi and Kanada-En'yo PRC 89 024315

α

$^{8}C_{gs} \rightarrow 4p + \alpha$ Γ= 130 (50) keV

PRC 84 (2011) 014320

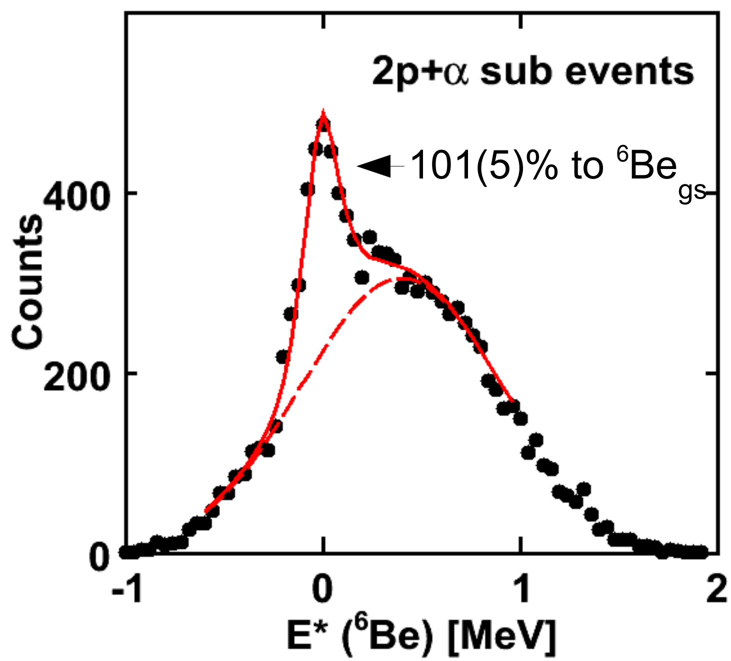


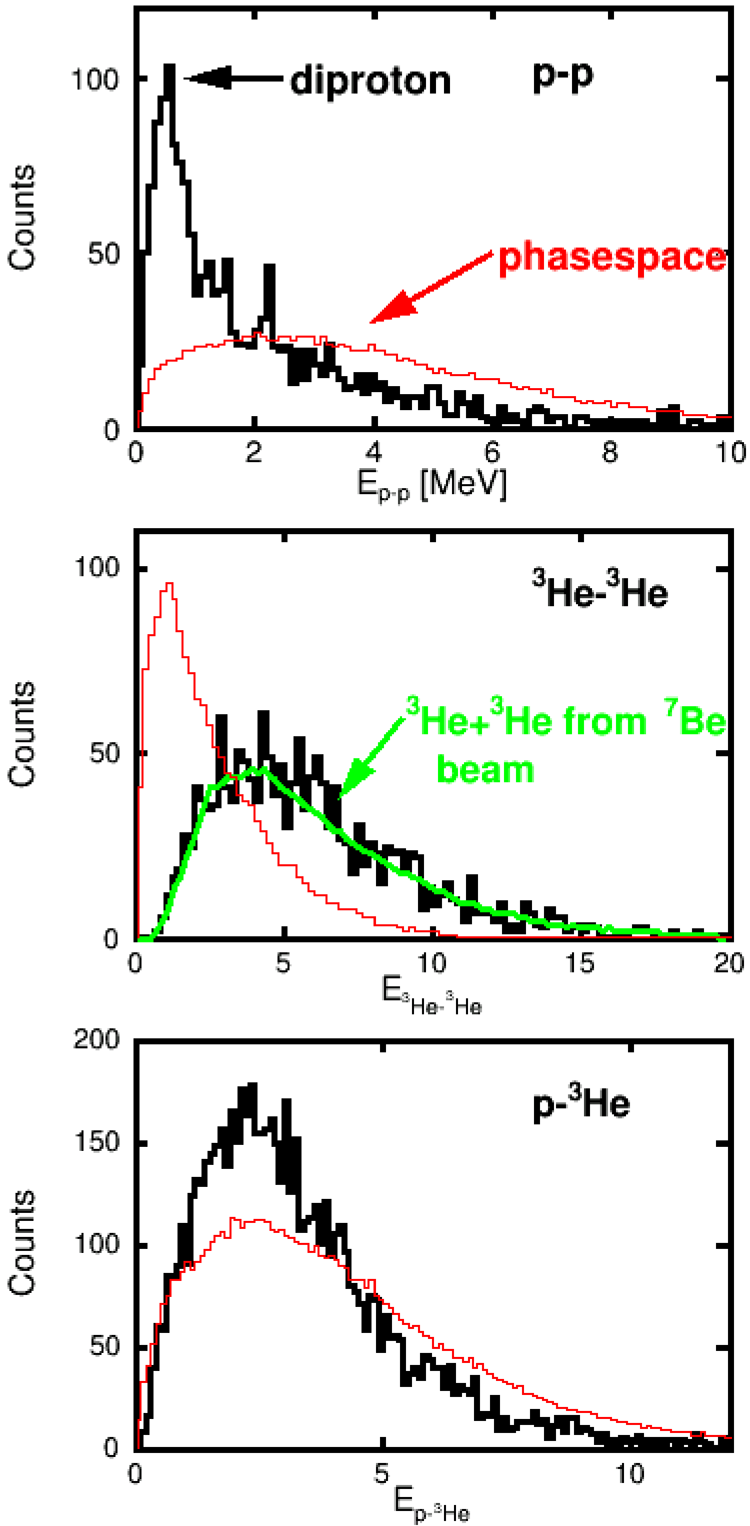


Complex scaling Method
Myo, Kikuchi, Masui, and Kato
Prog. Part. Nucl. Phys 79 (2014) 1

$^{8}C_{gs}$

$2p+{}^{6}Be_{0+} \rightarrow$ SF=16%
$2p+{}^{6}Be_{2+} \rightarrow$ SF=75%



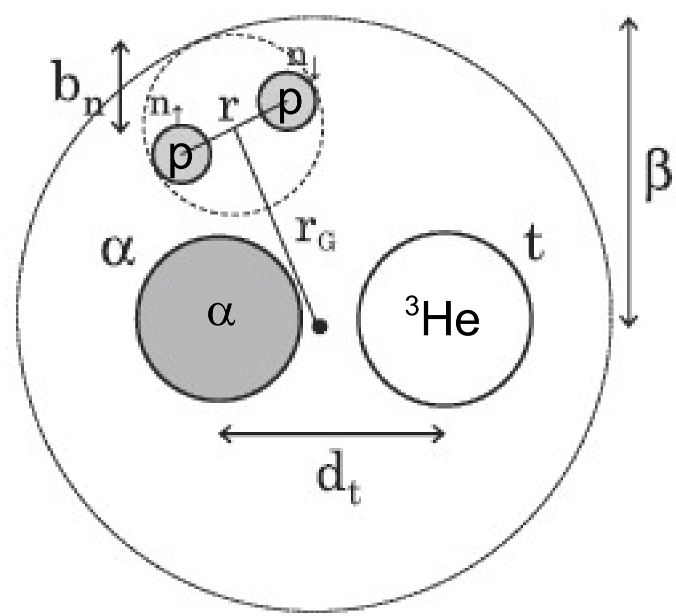


Correlations for the $2p + 2^3$He events

In the limit of extremely wide resonance,
Do we only see the structure of ^{9}C or
the structure of a wide ^{8}C resonance

1) strong diproton contribution

2) ^{3}He-^{3}He correlation is the same as observed for the ^{7}Be beam



^{9}C has important diproton + ^{7}Be structure?

Conclusions

a) elastic scattering measurement for protons on ^{14}O and ^{20}O to be made for DOM analysis of Oxygen isotopes

b) elastic scattering and total xsec for neutrons on ^{112}S and ^{124}Sn to be made for DOM analysis

c) Invariant-mass spectroscopy is a powerful tool to study structure in light nuclei

d) decay of narrow resonances is independent of the reaction mechanism

e) 3-body decay of ^{6}Be, ^{16}Ne states well described by $2p$+core model of Grigorenko

f) $^{8}C_{gs}$ decays by two-proton decay to $^{6}Be_{gs}$

g) $2p+2^{3}He$ channels probing the wavefunction of ^{9}C?