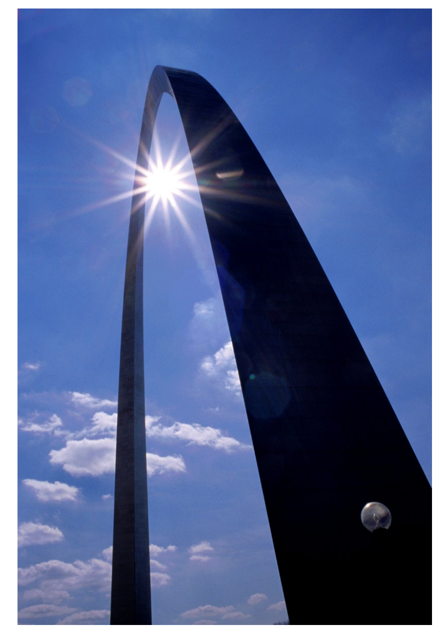
Continuum Spectroscopy of Light Nuclei

Robert Charity

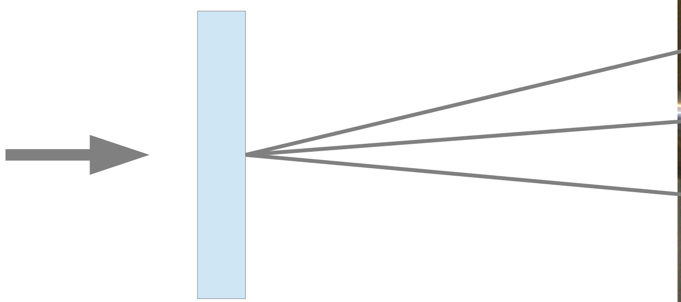
Washington University in St. Louis

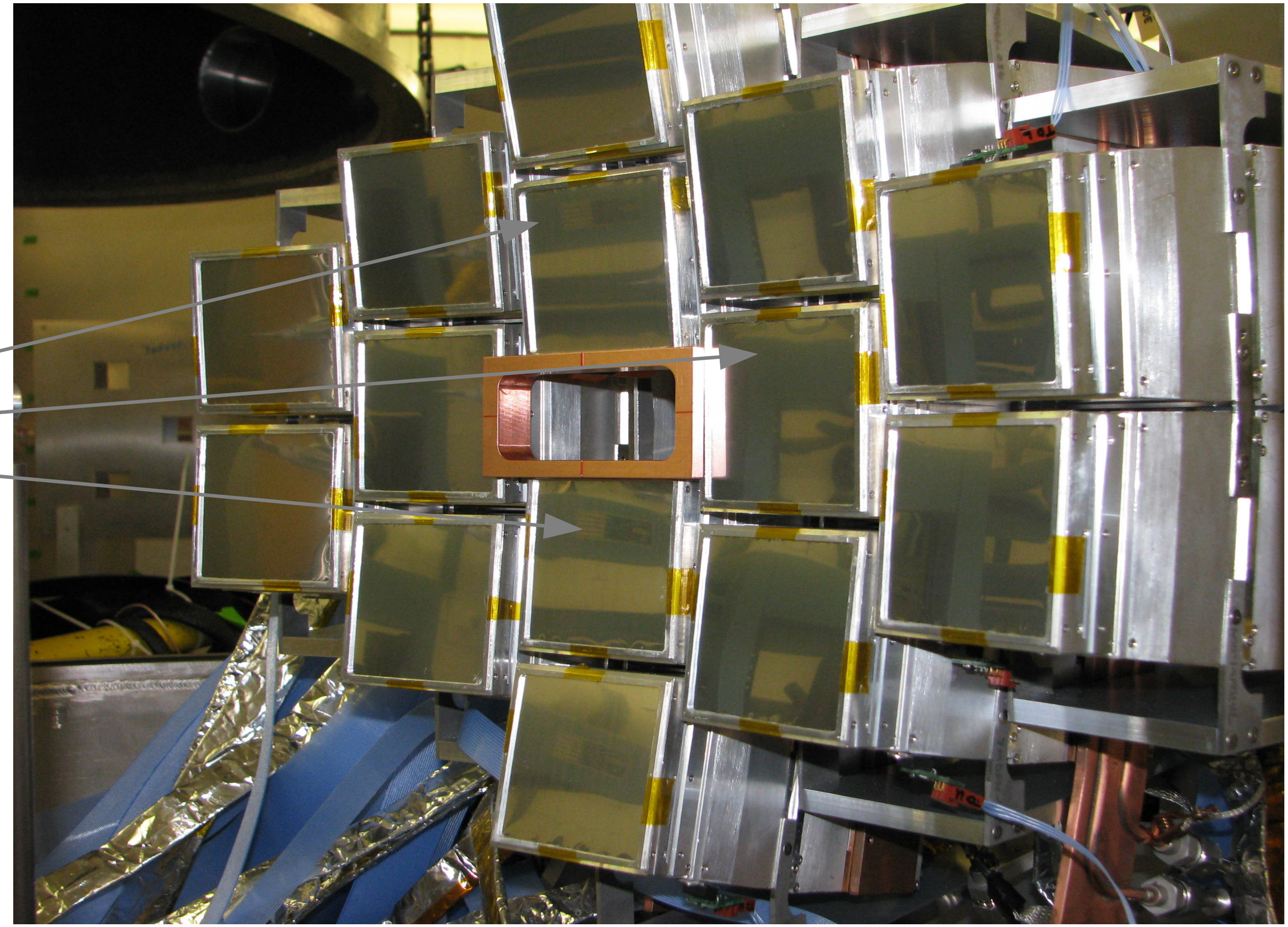


Nucleus-Nucleus 2015, catania

High Resolution Array.

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

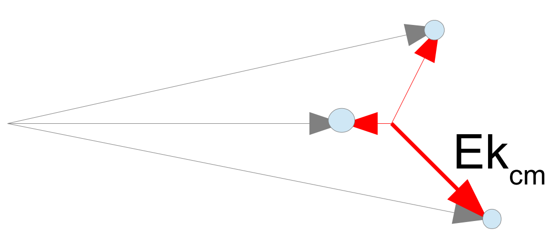




Parent nucleus decays in target.
Detect decay products in HiRA.
Need high angular resolution
(Si Strips)

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

Si-CsI E-ΔE telescopes



Invariant Mass Method

$$M_{inv} = \sum_i Ek^i_{cm} + M^i . \quad \text{decay energy } E_T = \sum_i Ek^i_{cm}$$

$$E^* = M_{inv} - M_{g.s.} = E_T - Q_{breakup}$$

An example of we get from an experiment proton-rich projectile

E/A=70 MeV ^{9}C + ^{9}Be reaction with HiRA

Found so far 42 resonances in $^{5,6,7}Li$, $^{6,7,8}Be$, $^{7,8,9}B$ and $^{8,9,10}C$ with charged-particle exit channels

These consist of

21 2-body exit channels
13 3-body exit channels (sequential and prompt decays)
7 4-body exit channels $2p+d+\alpha$, $p+\alpha+^{3}He$, $2p+2\alpha$,
1 5-body exit channels $4p+\alpha$

Most of these were known (can be used to check energy and angular calibration and simulations of detector resolution.)

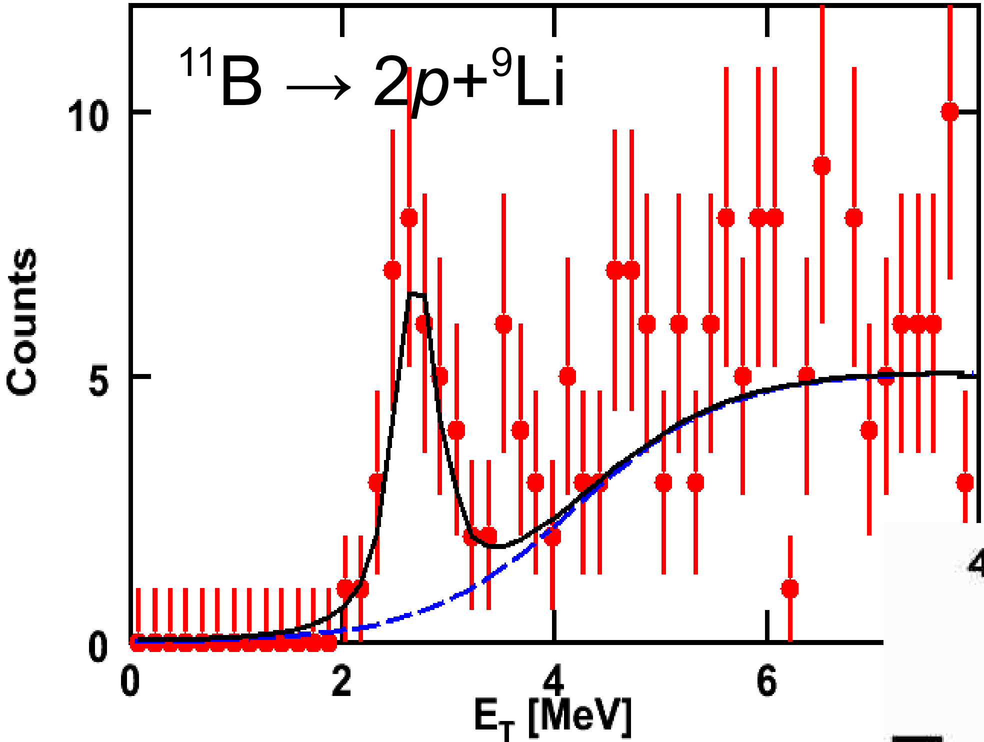
These include 6 previously unknown states
and 14 cases where the resonance was previously known
but we provided new information. (excitation energy, width, spin, decay path, branching ratios).

Large number of 3-body and greater exit channels.
Lower efficiency biases against these.

With neutron-rich beams we see lots of high T states

Double Isobaric analog of ^{11}Li in ^{11}B (T=5/2)

^{12}Be beam @E/A= 50 MeV with polyethylene target. ^{12}Be(p,2n)^{11}B

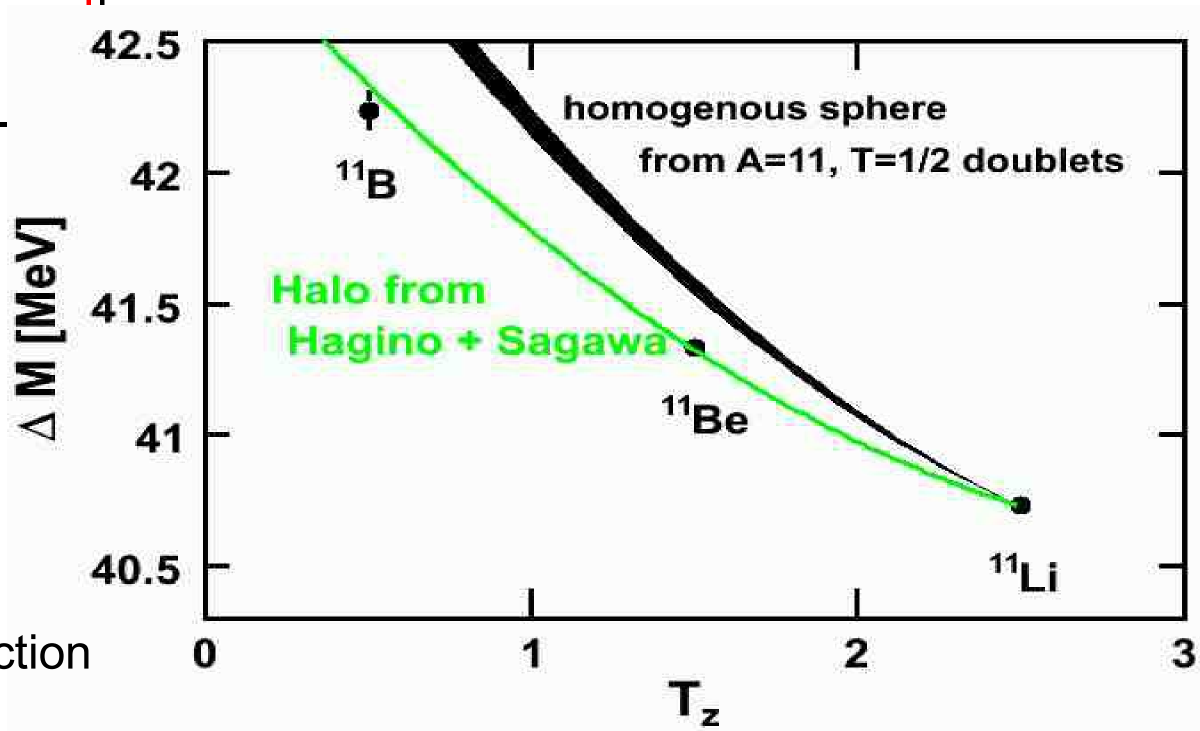


Decay kinetic energy

E*=33.6 MeV
E_T=2.70(8) MeV
Γ=306(182) keV

Fit include detector resolution

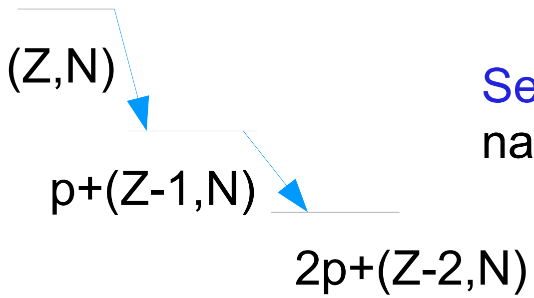
Exit-channel selectivity allows us to pick out this level from the high level density of low T states,



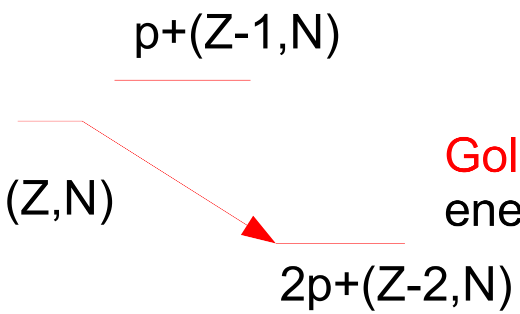
Isobaric Multiplet Mass Equation
Used to predict ^{11}O mass.
Extraploation using ^{11}Li halo wavefunction
of Hagino and Sagawa [P(s^2)=0.23

3 , 4 , 5-body exits channels: Prompt or Sequential?

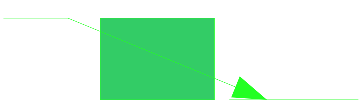
Look at 2*p* decay for example



Sequential,
narrow intermediate state $^{10}C^*$



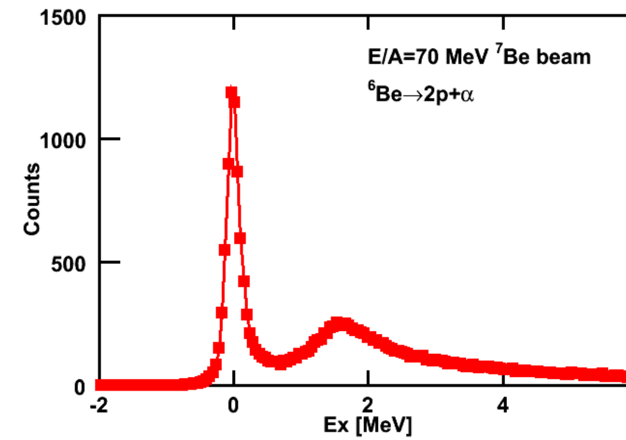
Goldansky (1960) (^{45}Fe, ^{48}Ni) intermediate energetically not reachable.

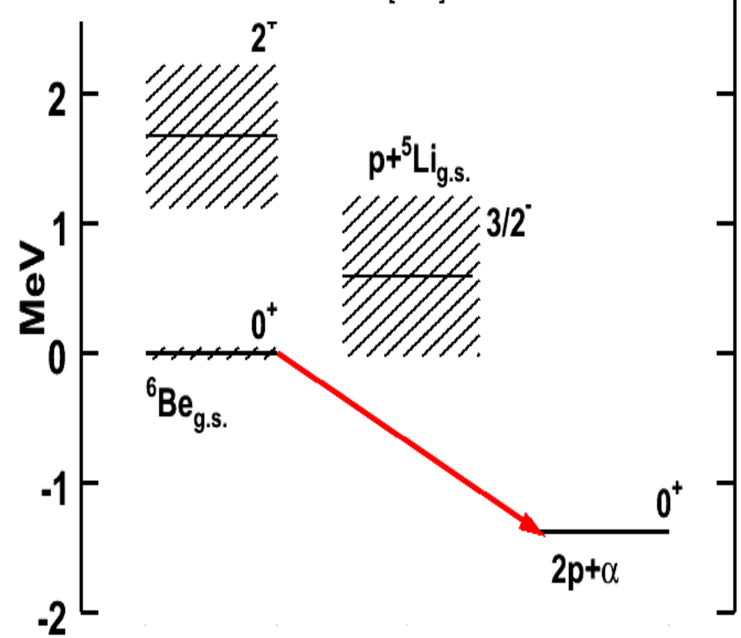


Bochkarev et al (1989) Democratic
(energy of prospective
1st proton is similar to width of
intermediate state)
wide intermediate state
Lifetime too short and so must
treat as prompt 2*p* decay.

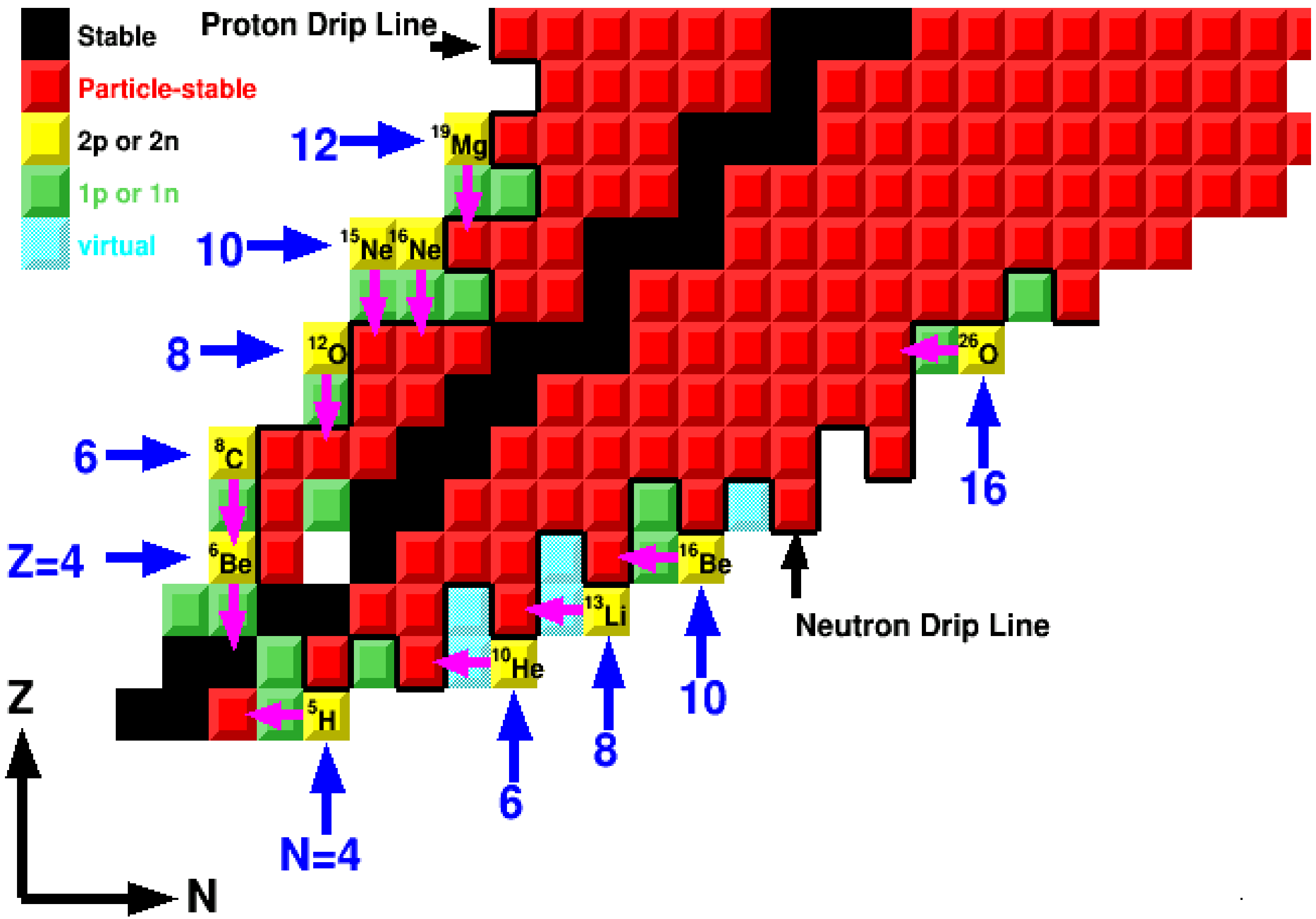
Pairing interaction responsible for both
Goldansky and Democratic decay. (even Z)

All light-nucleus have aspects of both Goldansky and Democratic
e.g. ^{6}Be



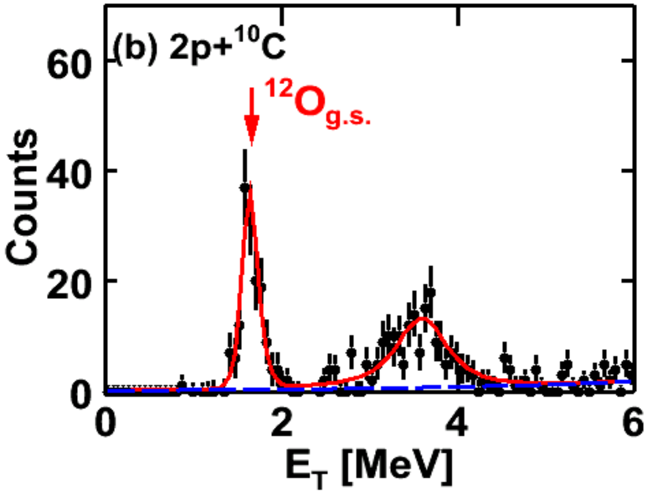


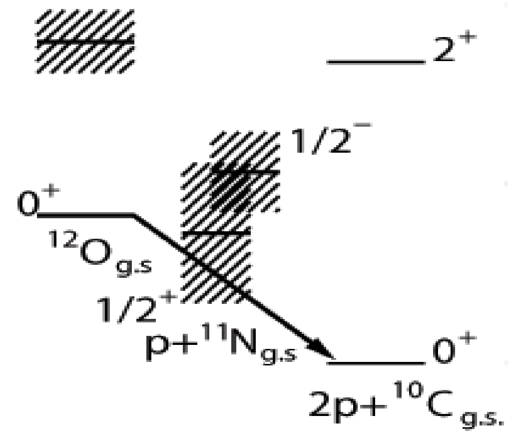
Systematics of light ground-state proton and neutron emitters



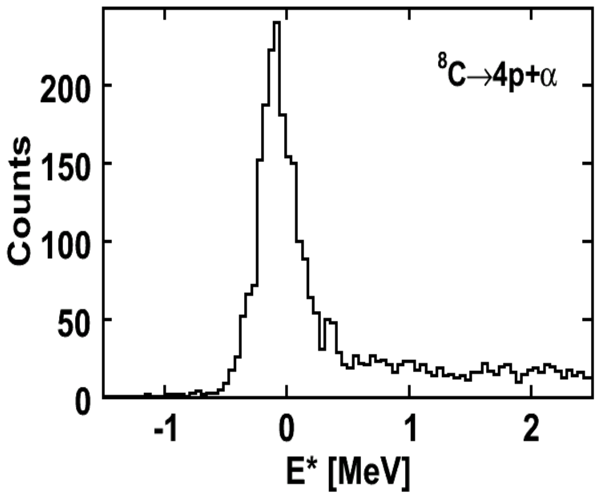
Odd-even dependence of ground state two-nucleon emitters

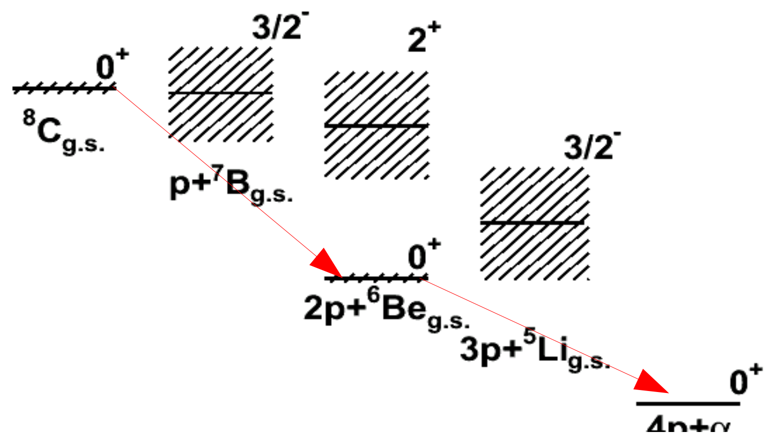
Form two-proton emitters from neutron knockout reactions



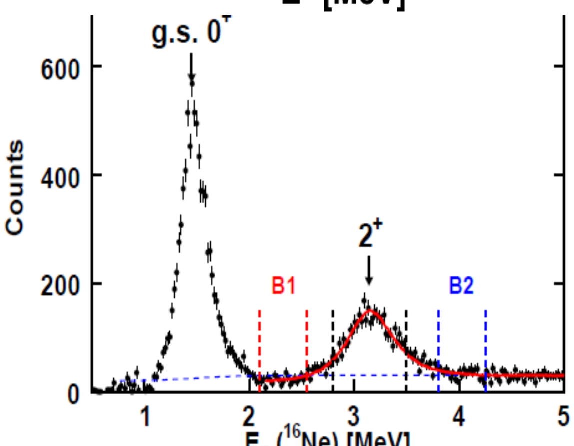


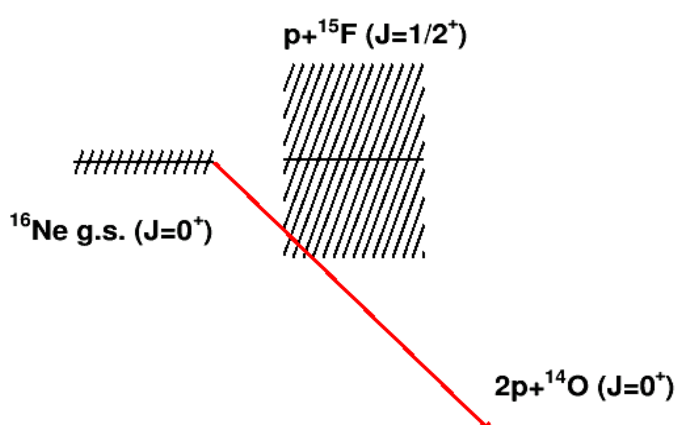
30 MeV/A
^{13}O beam@Texas A&M





70 MeV/A
^{9}C beam @NSCL





60 MeV/A
^{17}Ne beam@NSCL

Correlations between the momenta of the exit products in 3-body decay

Start:
3 fragments each with a momentum vector = 9 degrees of freedom

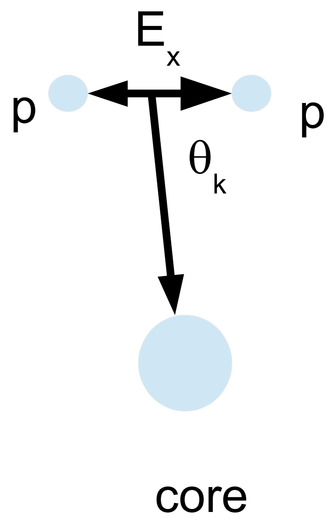
Remove:

a) center-of-mass motion	3 degrees of freedom
b) fixed decay energy (energy conservation)	1 degree of freedom
c) arbitrary rotation	3 Euler angles

Remainder = 2 degrees of freedom for correlations
The 2-dim distribution can gives us nuclear-structure and decay information.

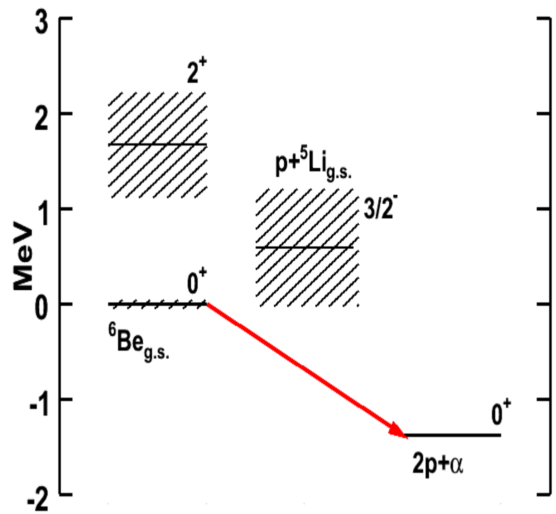
3-body decays can give more information than 2-body decays

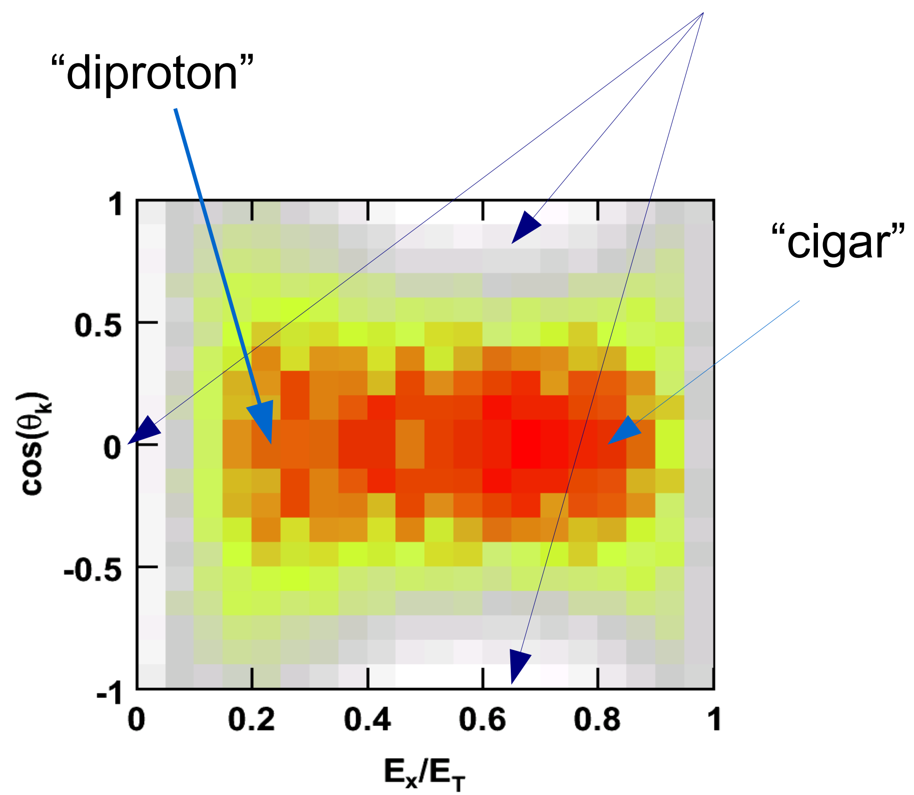
Jacobi T hyperspherical coordinates



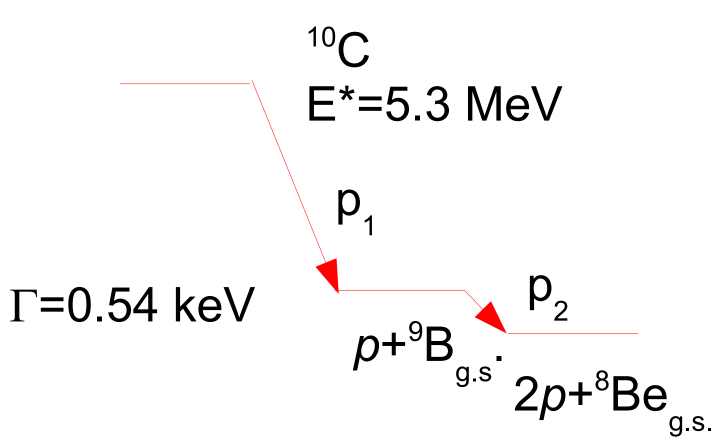
E_x - relative KE between 2 protons
E_T -total decay KE.

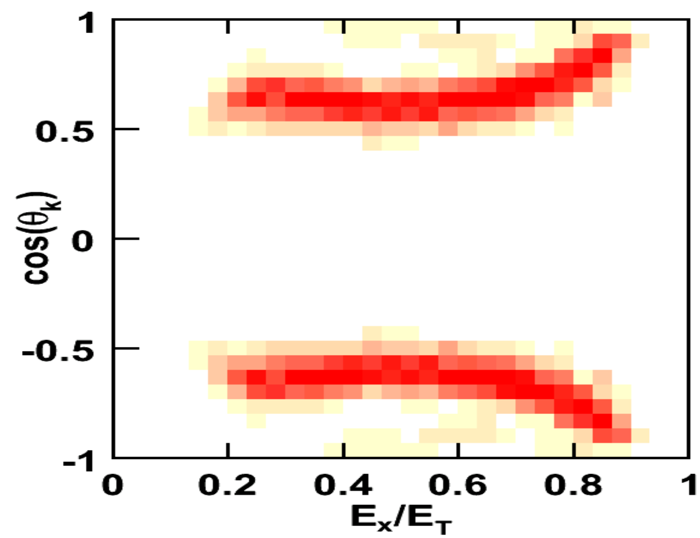
Prompt Decay



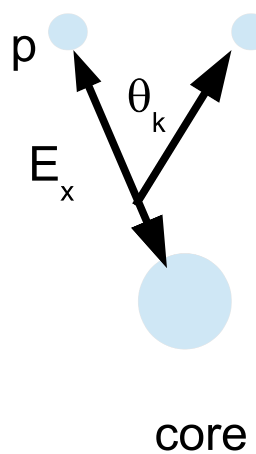


Sequential decay





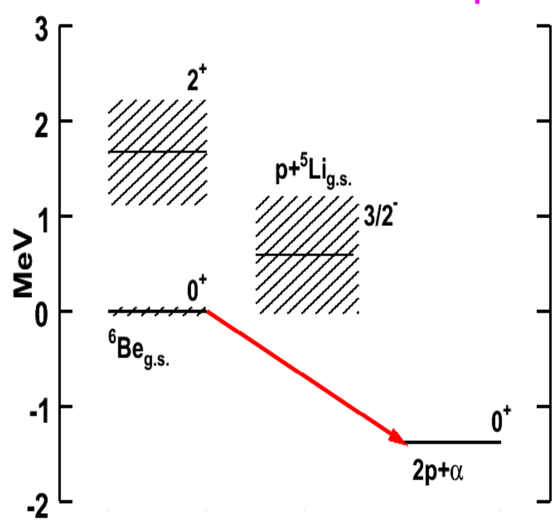
Jacobi Y hyperspherical coordinates

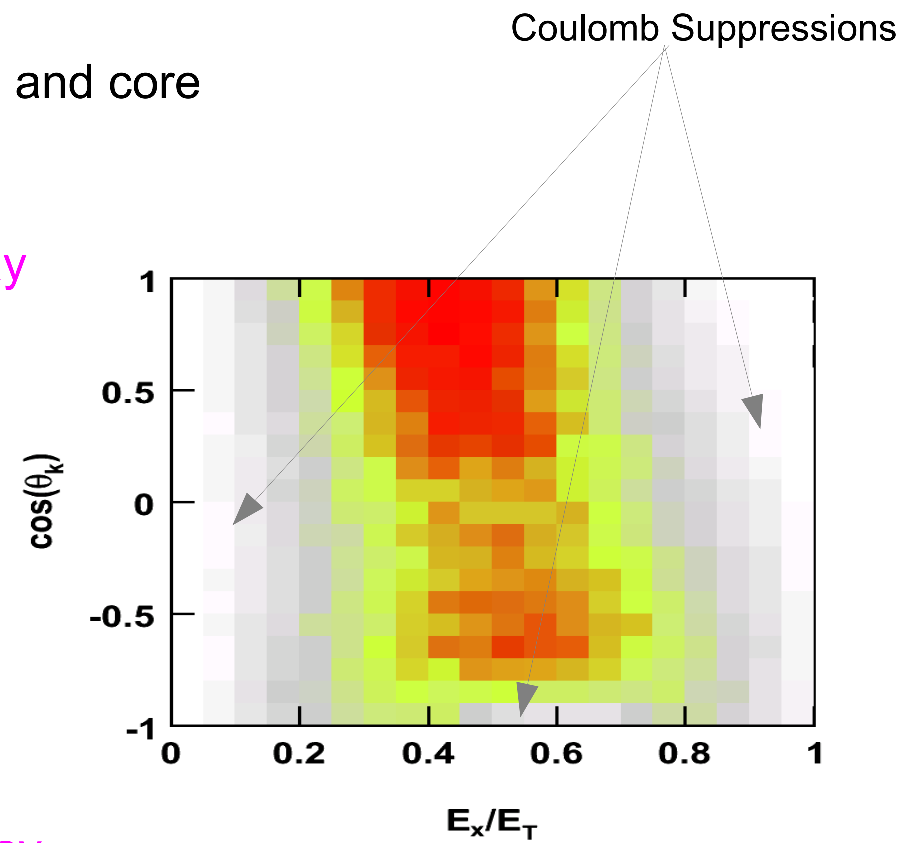


E_x- relative KE between proton and core

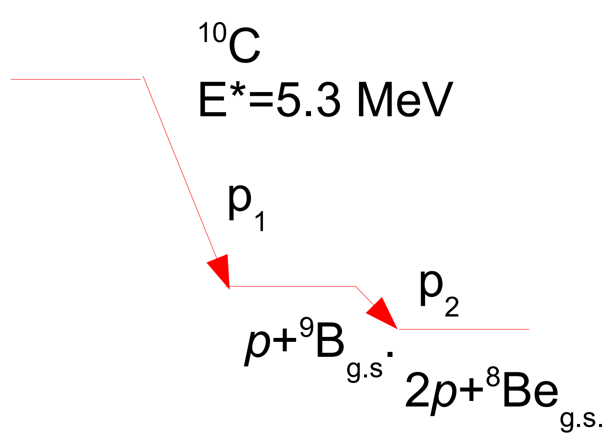
E_T -total decay KE.

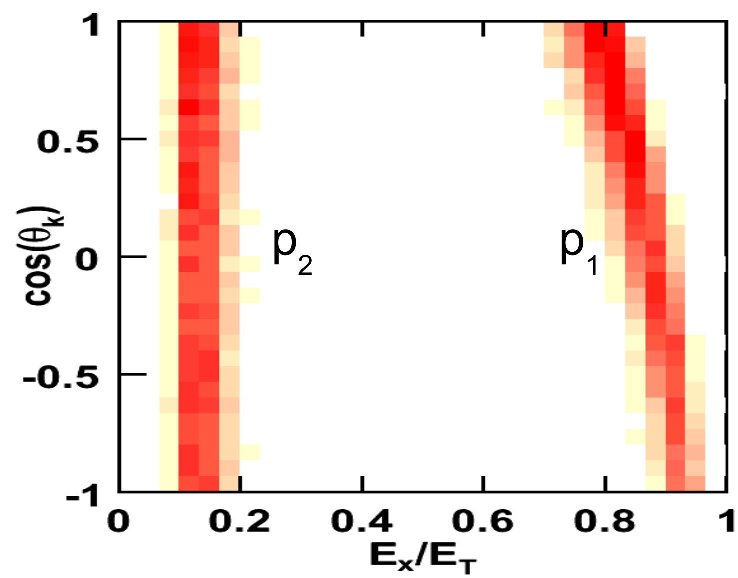
Prompt Decay





Sequential decay





Systematics of $E_{p\text{-}core} = E_x$ (Jacobi Y)

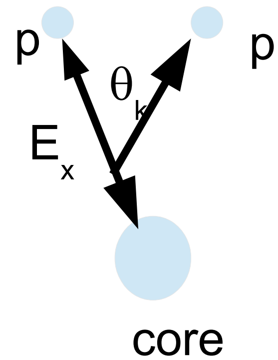
a) Less dependent of calculation details

b) Less dependent on detector bias

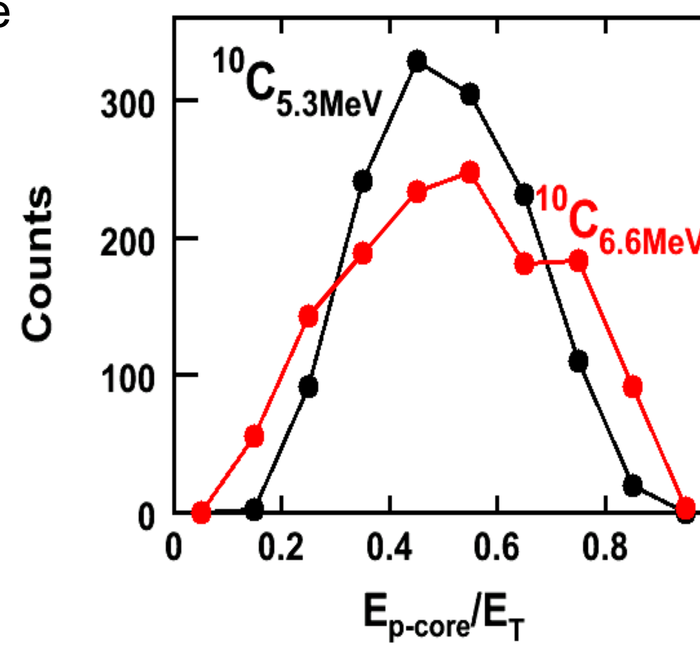
c) Goldansky $\sim P(E_x)P(E_T - E_x)$

Product of 2 penetration factors

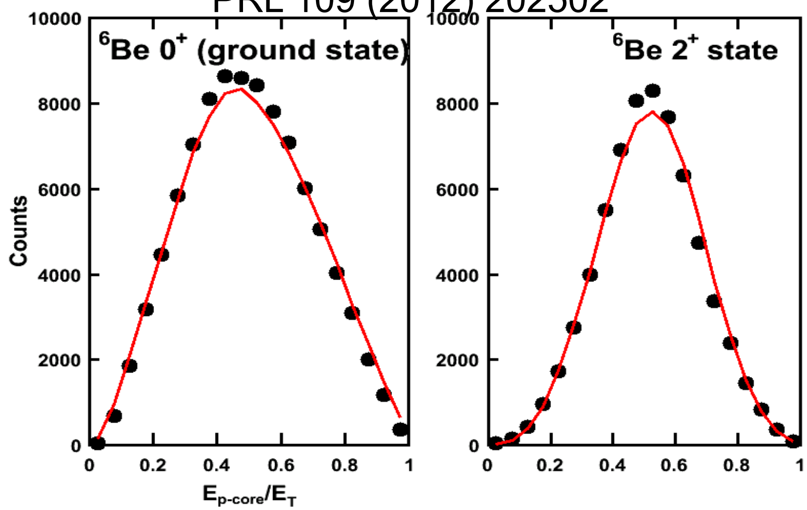
Peaks at $E_x = E_T/2$

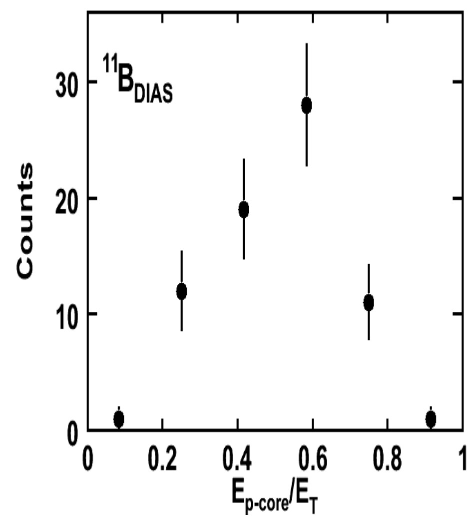


PRC 80 (2009) 024306

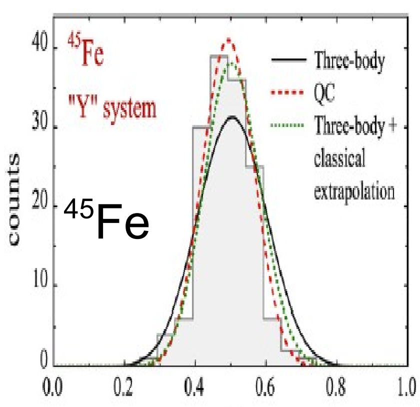


PRL 109 (2012) 202502

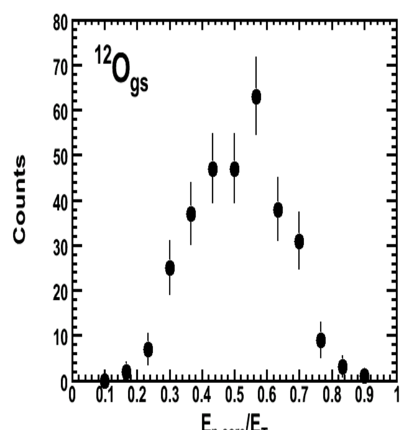




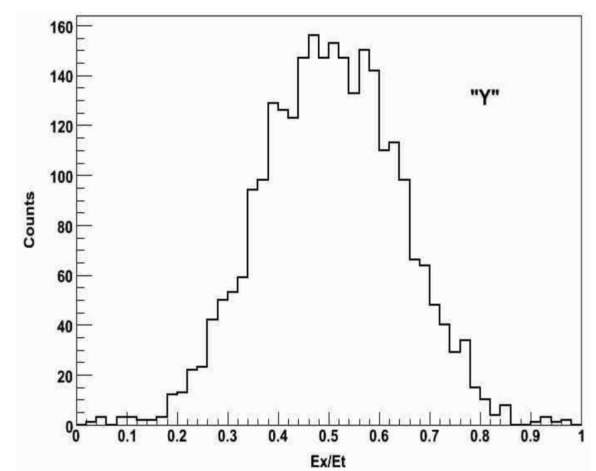
PRC 86 (2012) 041307.



PRL99(2007)192501

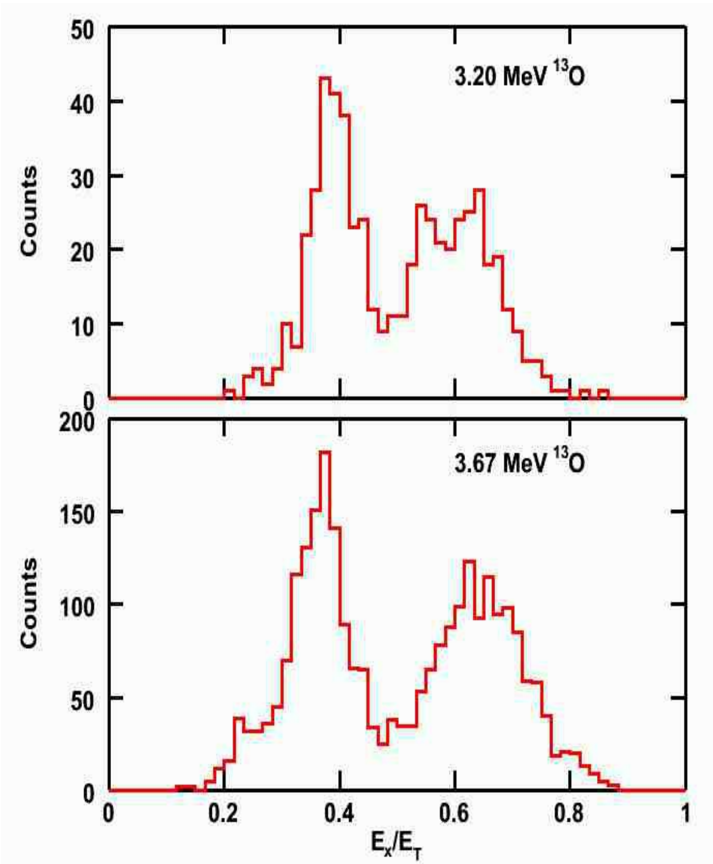


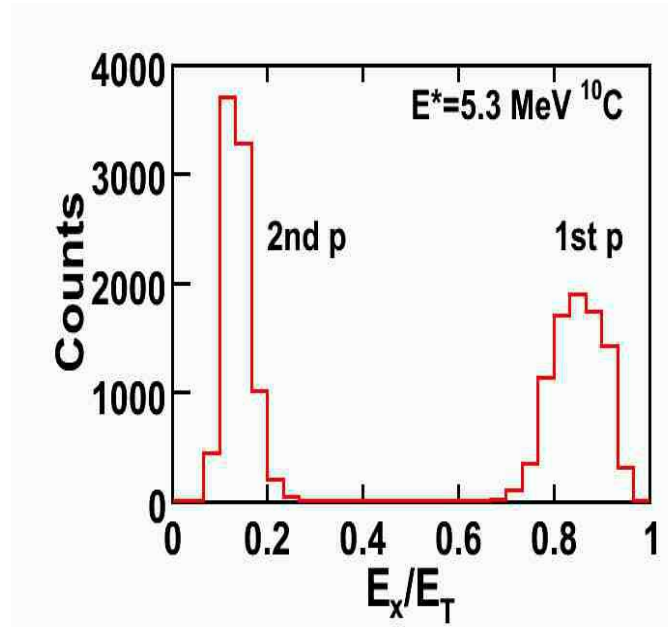
PRC 86 (2012) 011304R

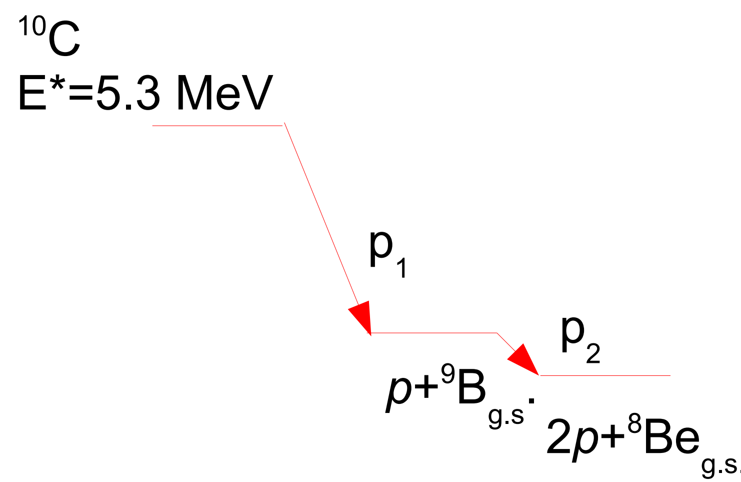


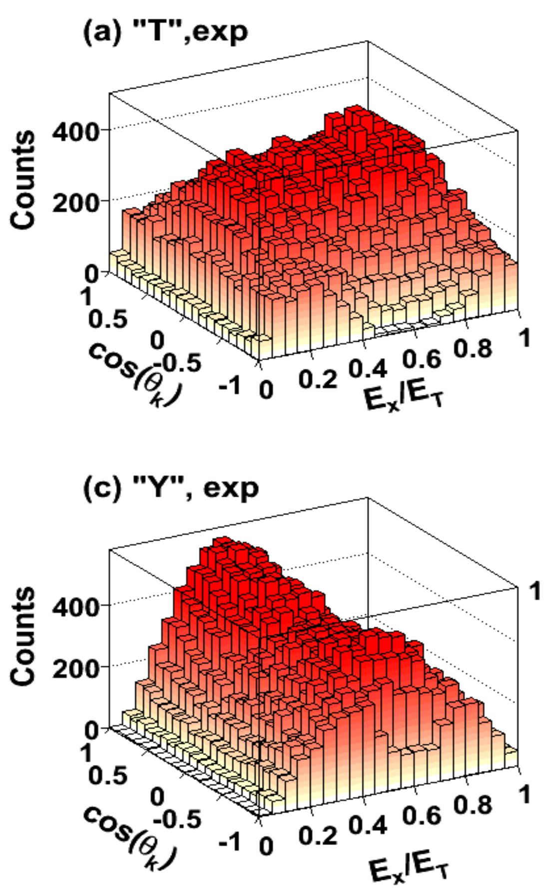
^{16}Ne ground state

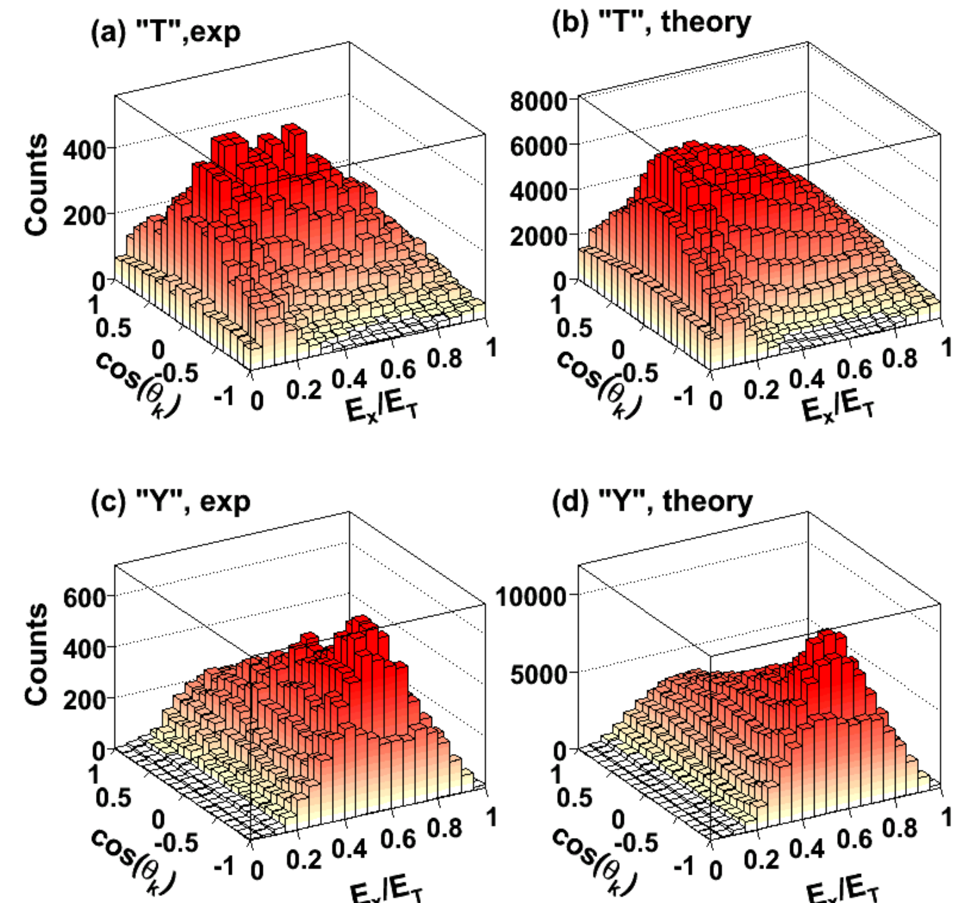
E_{core-p} (Jacobi y) for sequential decay





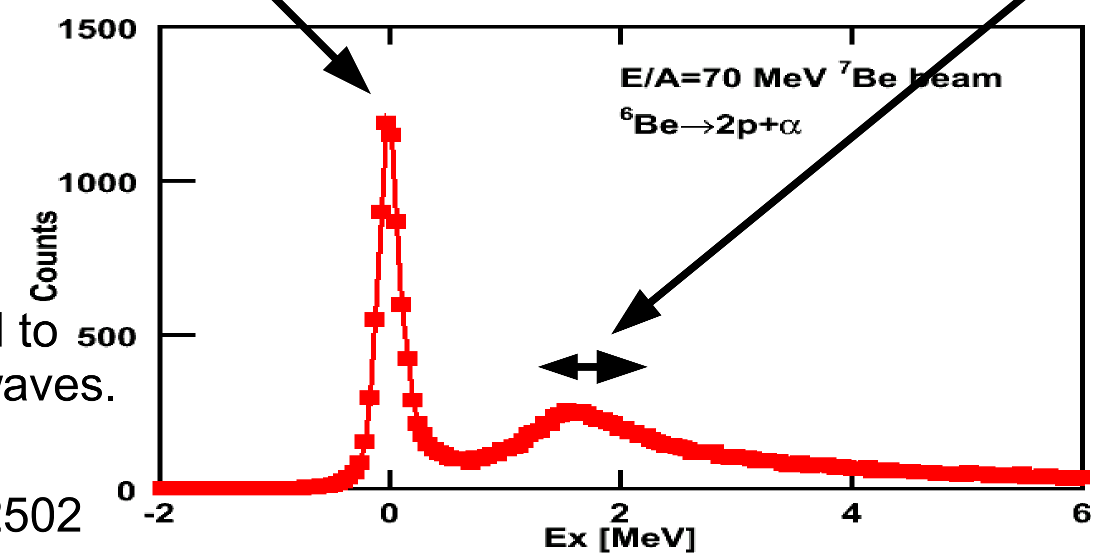


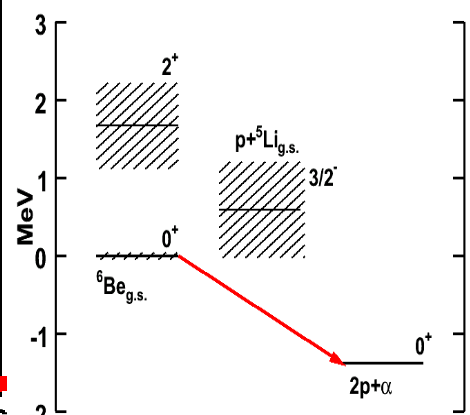




^{6}Be ground-state 0^+

^{6}Be 1st excited state 2^+





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

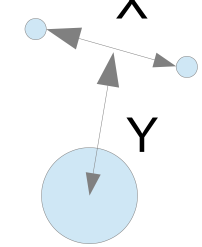
PRL 109 (2012) 202502

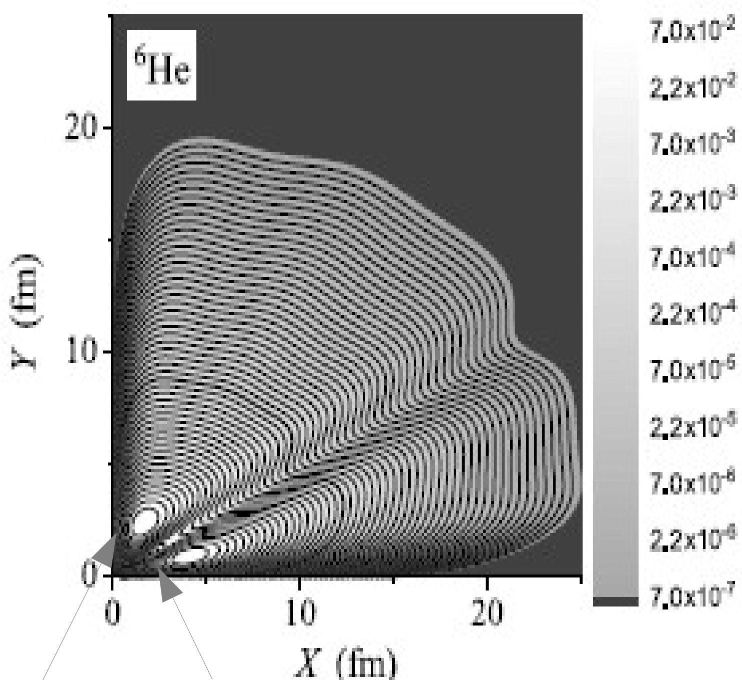
Cluster model ground-state wavefunctions , isospin symmetry of ^{6}He-^{6}Be mirror pair

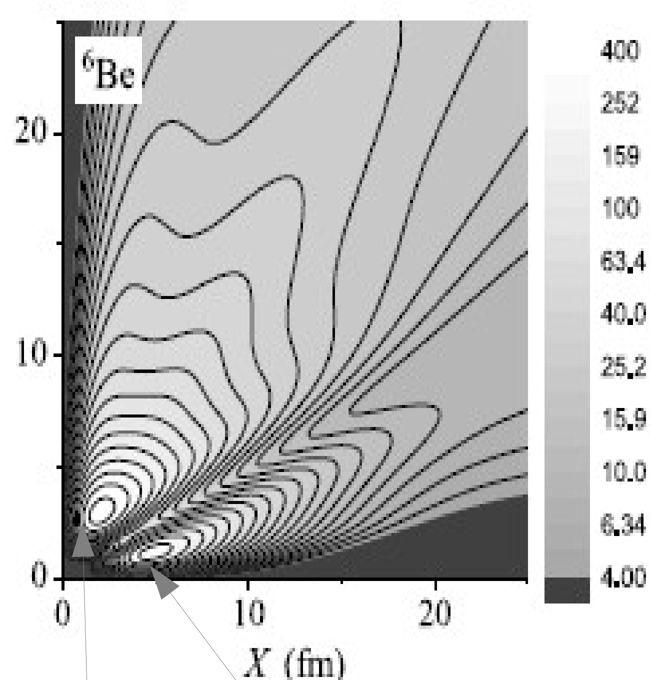
cigar

Dinucleon

Grigorenko PRC 80 (2009) 034602







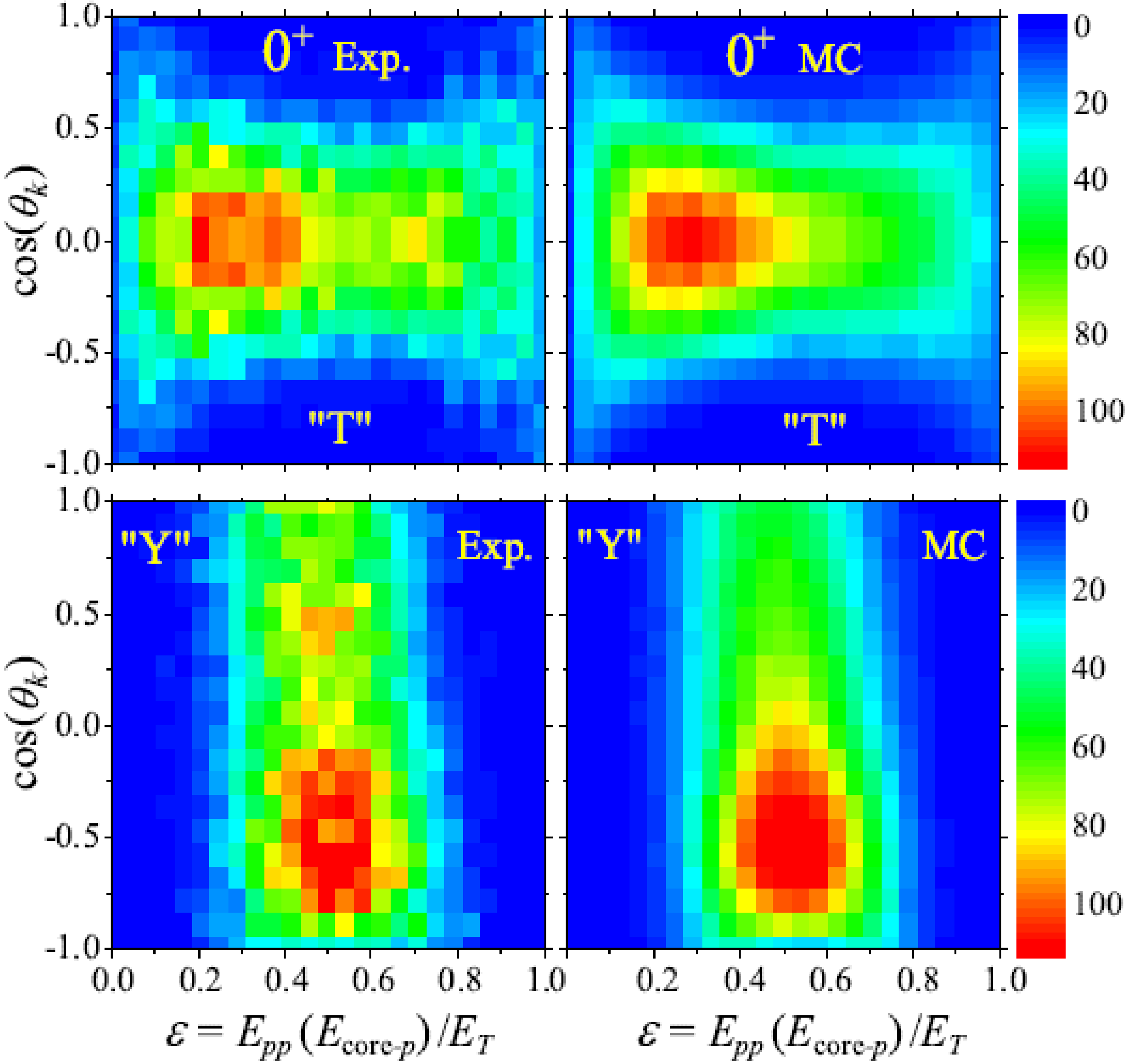
cigar

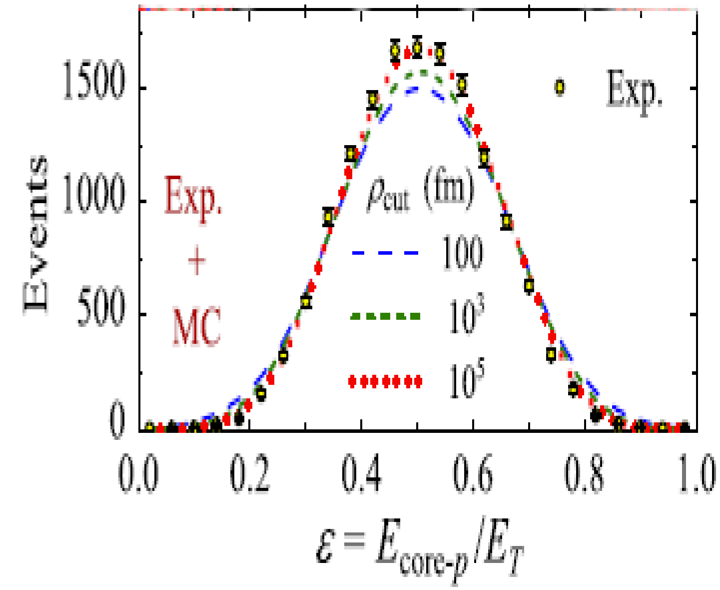
dineutron

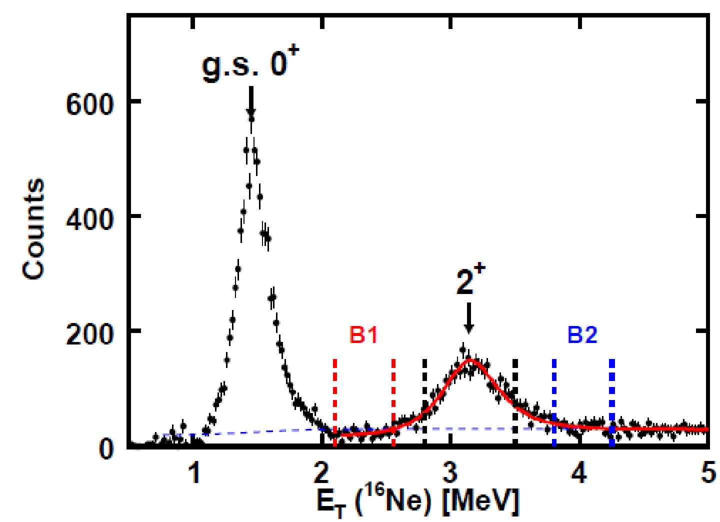
cigar

diproton

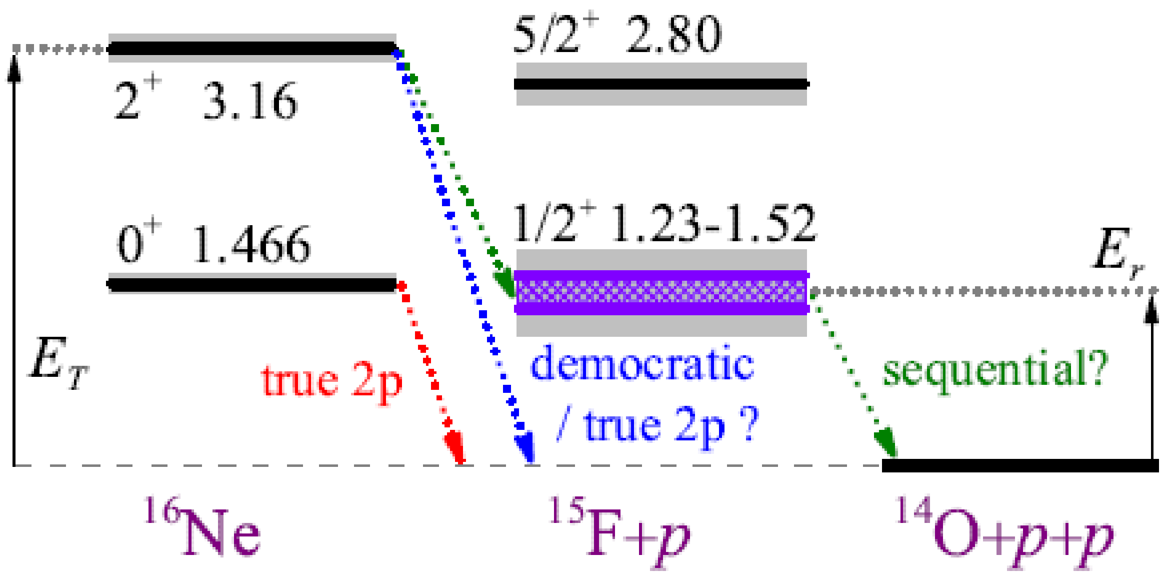
Comparison to Three-body model of Grigorenko et al. 16Ne ground state







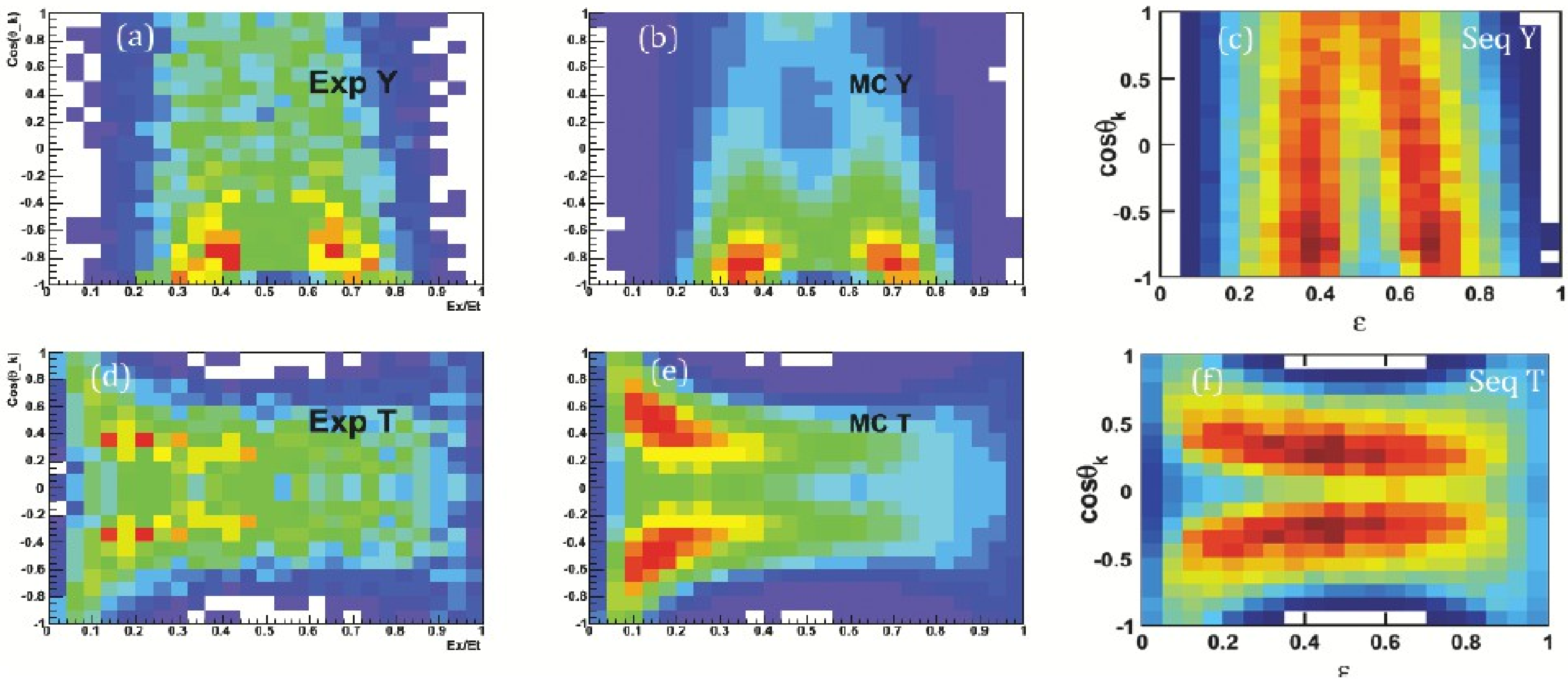
Transition from prompt to sequential with excitation energy?



Two-proton decay of first excited state no longer forfills the democratic condition that
The kinetic energy of the first proton is the same order as the width of the state.

Is the decay now sequential?

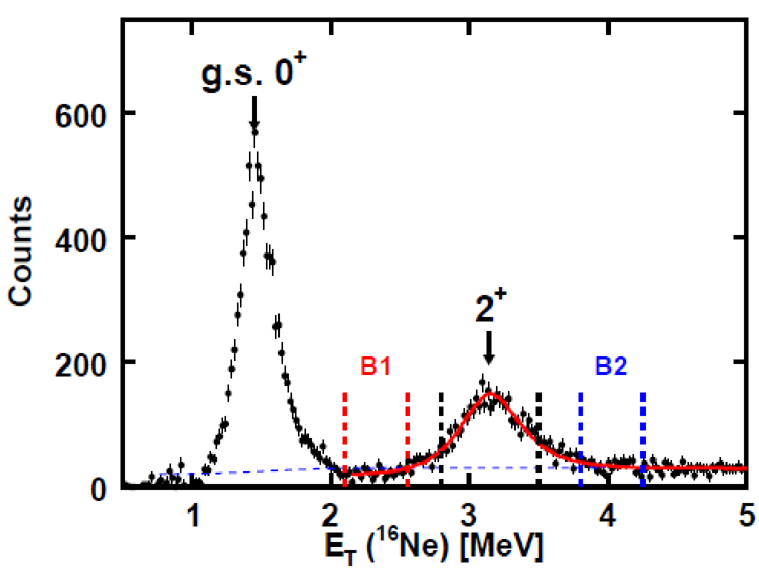
^{16}Ne first excited state J= 2^+

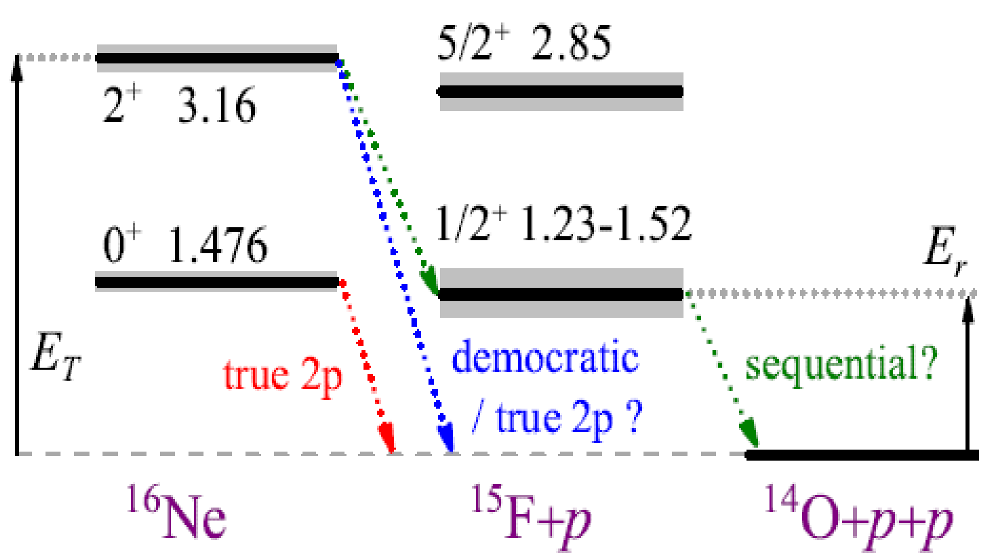


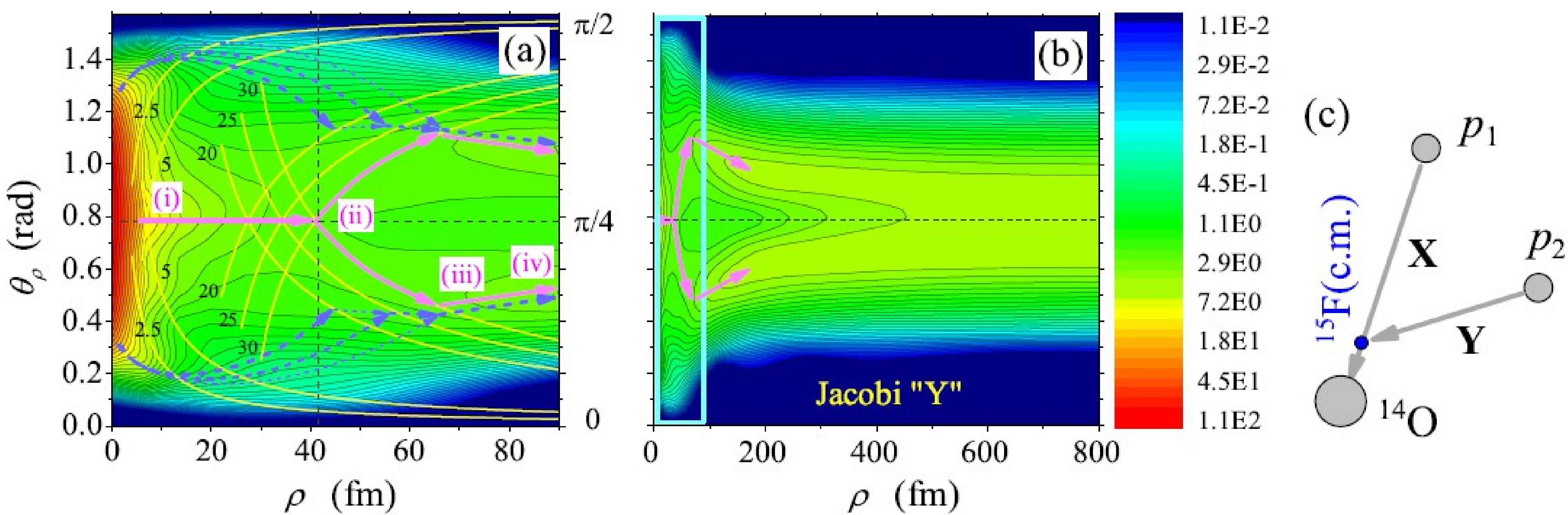
Jacobi Y

Jacobi T

experiment 3-body model sequential







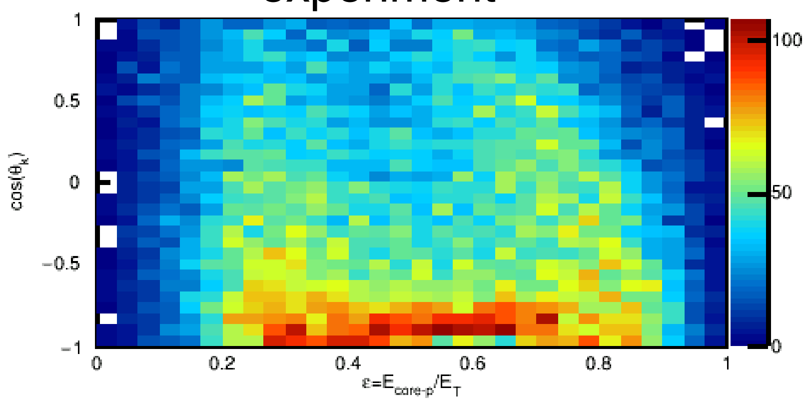
Three-cluster model wavefunctions suggests the strange correlations plots are a results of interference between prompt and sequential decay paths.

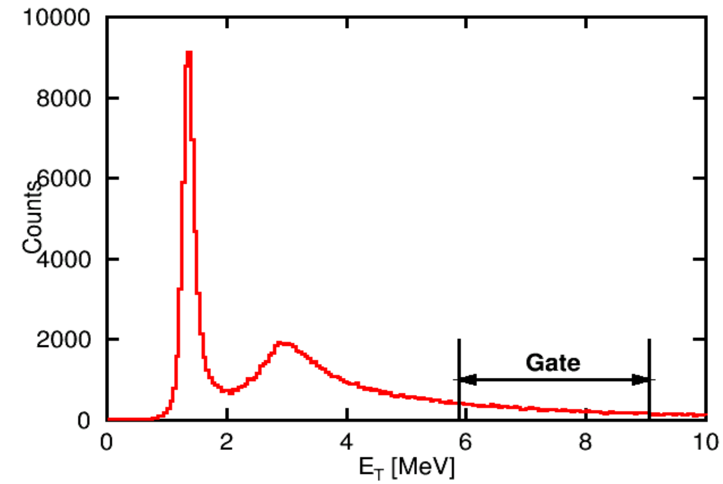
$$X = \rho \sqrt{\frac{A_{core}+1}{A_{core}}} \sin(\theta_\rho)$$

$$Y = \rho \sqrt{\frac{A_{core}+2}{A_{core}+1}} \cos(\theta_\rho)$$

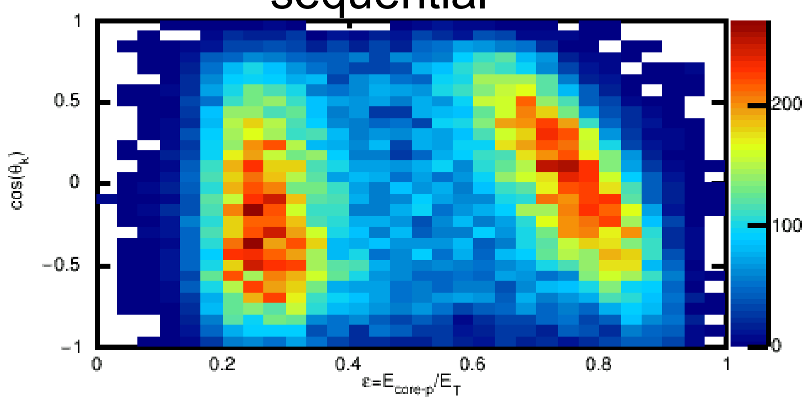
Tail of the ^{6}Be first excited state J = 2$^+$

experiment



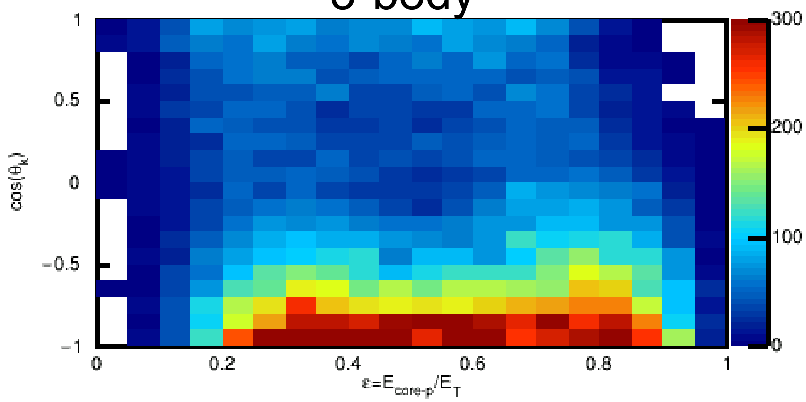


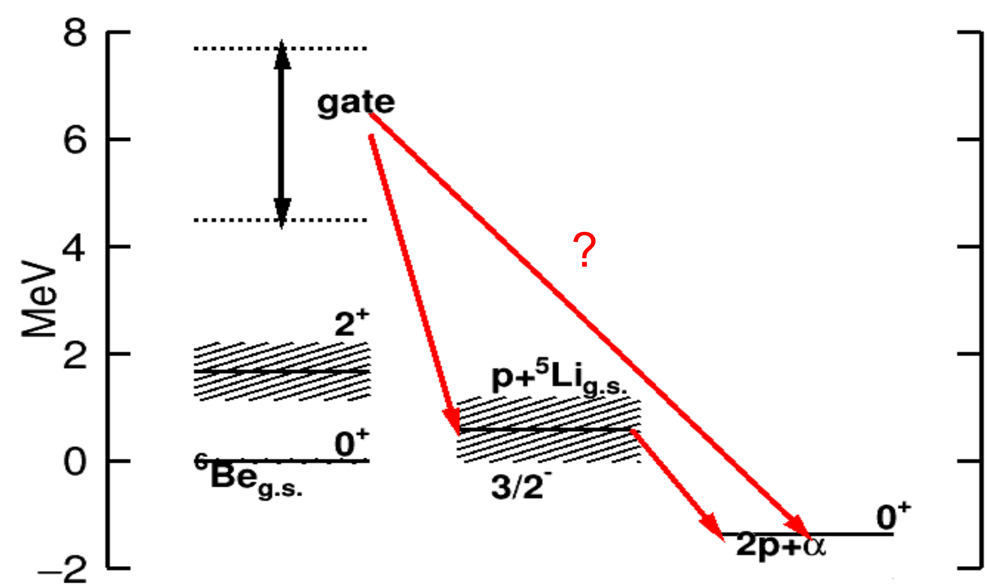
sequential



Jacobi Y

3-body





Conclusions

a) Invariant-mass spectroscopy is a valuable tool for detecting and understanding Resonances, especially those with exit channels with more than 3 particles.

b) Light ground-state nuclei beyond the proton drip line with even Z are two-proton emitters.

c) the momentum correlations between the decay fragments in 3-body decay give important information of the decay.

d) the excited states of ground-state two-proton emitters show a complicated emission pattern with aspects of both prompt and sequential decay.

PRL 113, 232501 (2014) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2014

Observation of Long-Range Three-Body Coulomb Effects in the Decay of ^{16}Ne

K. W. Brown,[1] R. J. Charity,[1] L. G. Sobotka,[1] Z. Chajecki,[2] L. V. Grigorenko,[3,4] I. A. Egorova,[5] Yu. L. Parfenova,[3,6] M. V. Zhukov,[7] S. Bedoor,[8] W. W. Buhro,[2] J. M. Elson,[1] W. G. Lynch,[2] J. Manfredi,[2] D. G. McNeel,[8] W. Reviol,[1] R. Shane,[2] R. H. Showalter,[2] M. B. Tsang,[2] J. R. Winkelbauer,[2] and A. H. Wuosmaa[8]

[1]*Departments of Chemistry and Physics, Washington University, Saint Louis, Missouri 63130, USA*
[2]*National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Flerov Laboratory of Nuclear Reactions, JINR, RU-141980 Dubna, Russia*
[4]*Russian Research Center "The Kurchatov Institute", Kurchatov square 1, RU-123182 Moscow, Russia*
[5]*Bogoliubov Laboratory of Theoretical Physics, JINR, RU-141980 Dubna, Russia*
[6]*Skobel'tsyn Institute of Nuclear Physics, Moscow State University, RU-119991 Moscow, Russia*
[7]*Fundamental Physics, Chalmers University of Technology, S-41296 Göteborg, Sweden*
[8]*Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008, USA*

(Received 11 June 2014; published 2 December 2014)