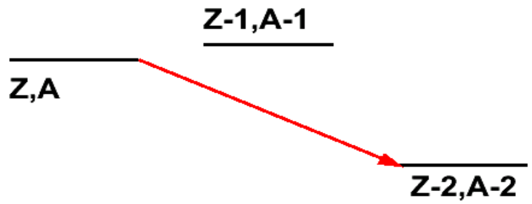
Two-Proton Decay Experiments

Robert Charity

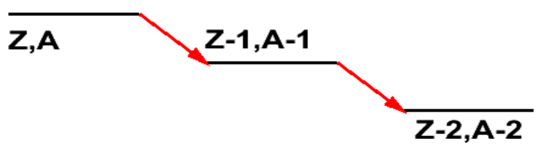
Washington University, St. Louis, USA

Washington University in St. Louis

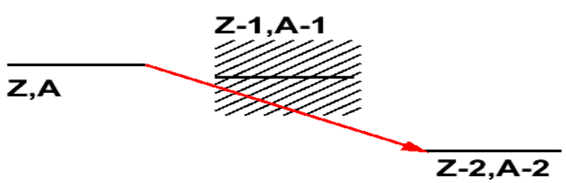
Classification of 2*p* decays



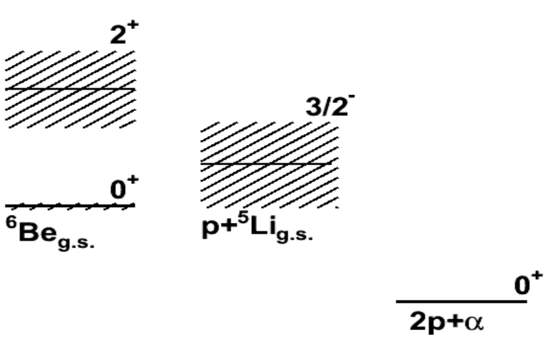
Goldansky (1960) 2*p* decay (like double β decay)
Intermediate state not accessible to 1*p* decay.
^{45}Fe, ^{48}Ni, ^{54}Zn



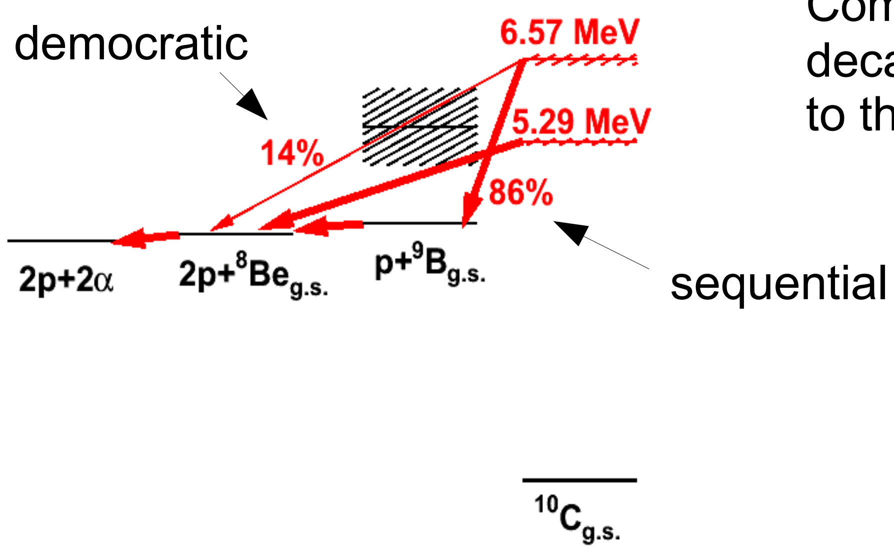
Sequential 2*p* decay



Democratic 2*p* decay (Bochkarev et al) (1986)
Lifetime of intermediate state too short to be sequential. (^{6}Be, ^{8}C) No sharp boundary between sequential and Democratic



Reality can be more complex
^{6}Be – Democratic and Goldansky?
or almost Goldansky
Barker – width of ^{6}Be not explained by sequential 2*p* decay (*R*matrix)



Competing sequential and democratic decay paths in ^{10}C, strong diproton character to the 3-body branch

Two – Proton Emitters
Large range of lifetimes.

Ground states

Short lived
$t_{1/2} < 10^{-20}$ s
^{6}Be
^{8}C
^{12}O
^{16}Ne

^{19}Mg $t_{1/2}$ = 4 ps

Long lived
$t_{1/2} > 1$ ms
^{45}Fe
^{48}Ni
^{54}Zn

Possible candidates
^{26}S
^{30}Ar
^{34}Ca

Excited states

^{8}B
^{10}C
^{18}Ne
^{17}Ne

Correlations in 2*p* decay

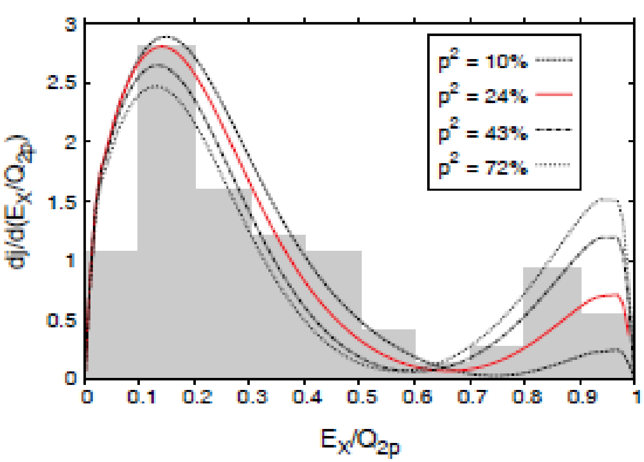
Information content from n-body decay

	2-body	3-body	4-body
Degree of freedom*	6	9	12
Momentum Conservation	-3	-3	-3
Energy Conservation	-1	-1	-1
Orientation	-2	-3	-3
Remaining	0	2	5

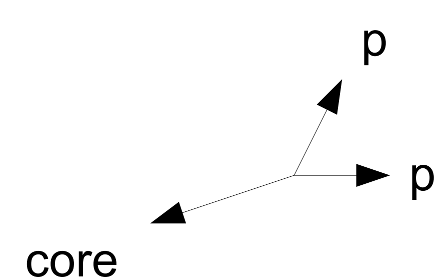
* - ignoring spin degrees of freedom

In β decay one uses the electron-neutrino correlations to contain theory (two parameters*)

Can we utilize the extra information from a three-body decay to learn more about the structure of the level. Need models of 3-body decay to compare to.



^{45}Fe
Miernik et al.
Eur. Phys. J. A42 (2009) 431



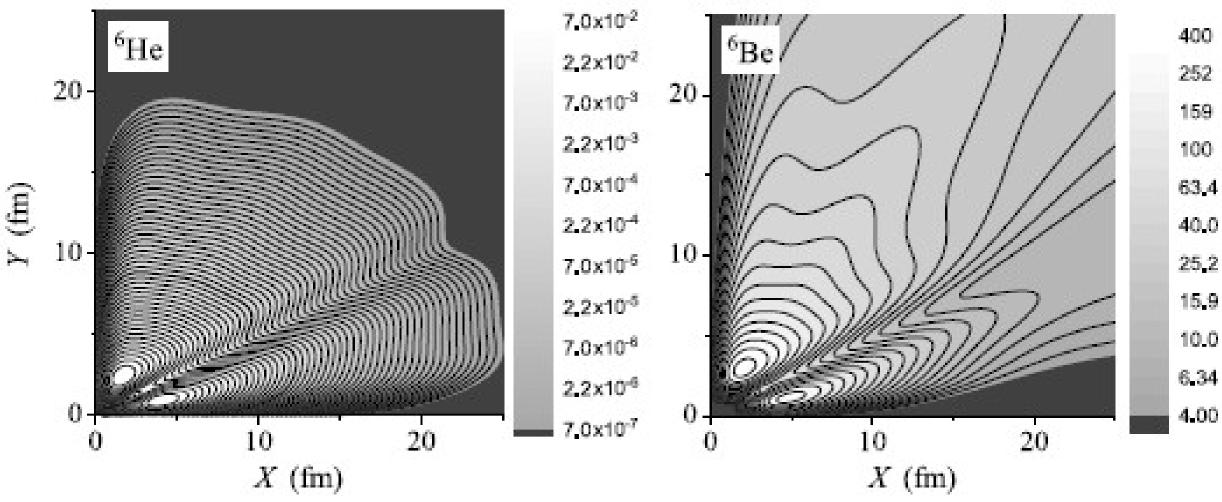
Relationship to 2-neutron-halo nuclei.

Mirror (2-*p* emitters) (2-*n* halo) systems

^{6}Be - ^{6}He
^{8}C - ^{8}He
^{11}O? - ^{11}Li

To experimental study *n-n* correlations in the halo, one needs a reaction to break up the system. Theoretically one needs a model for the reaction and a model for the structure.

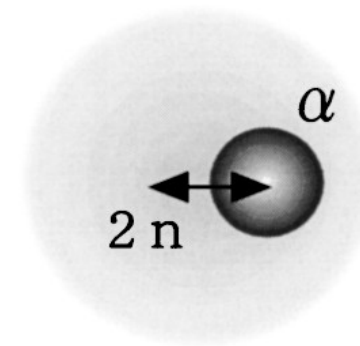
The 2-*p* decay of the mirror state can be studied in one model. Turning off the Coulomb interaction in such a model will give the *n-n* correlations.



Grigorenko et al PRC 80 (2009) 034602

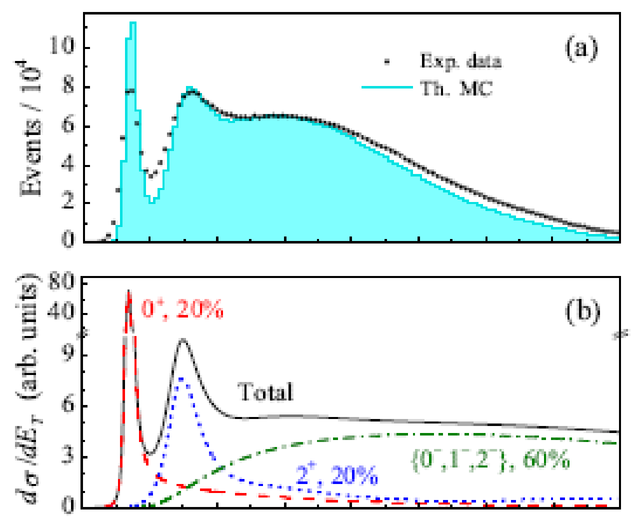
Soft Dipole Mode in Halo Nuclei

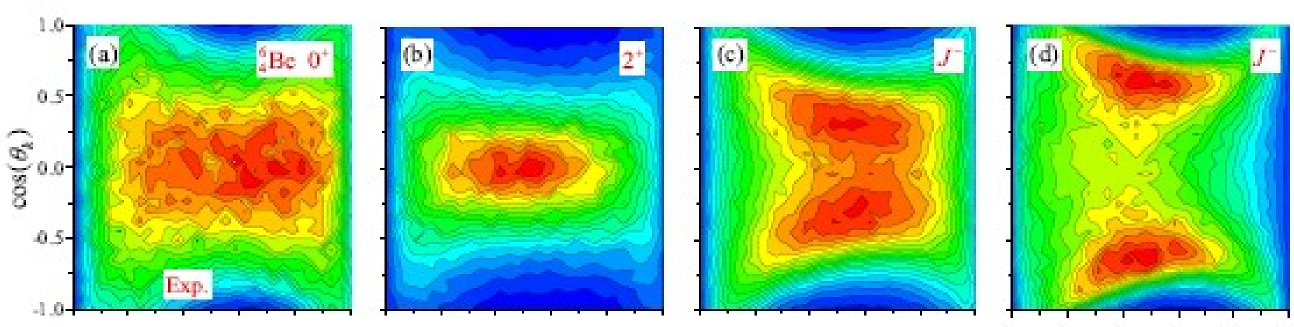
^{6}He core-halo vibration
Corresponding structure seen in ^{6}Be



"soft-DR"

Charge exchange *p*(^{6}Li,^{6}Be)*n*
Excites IVSDM.
Golovkov et al

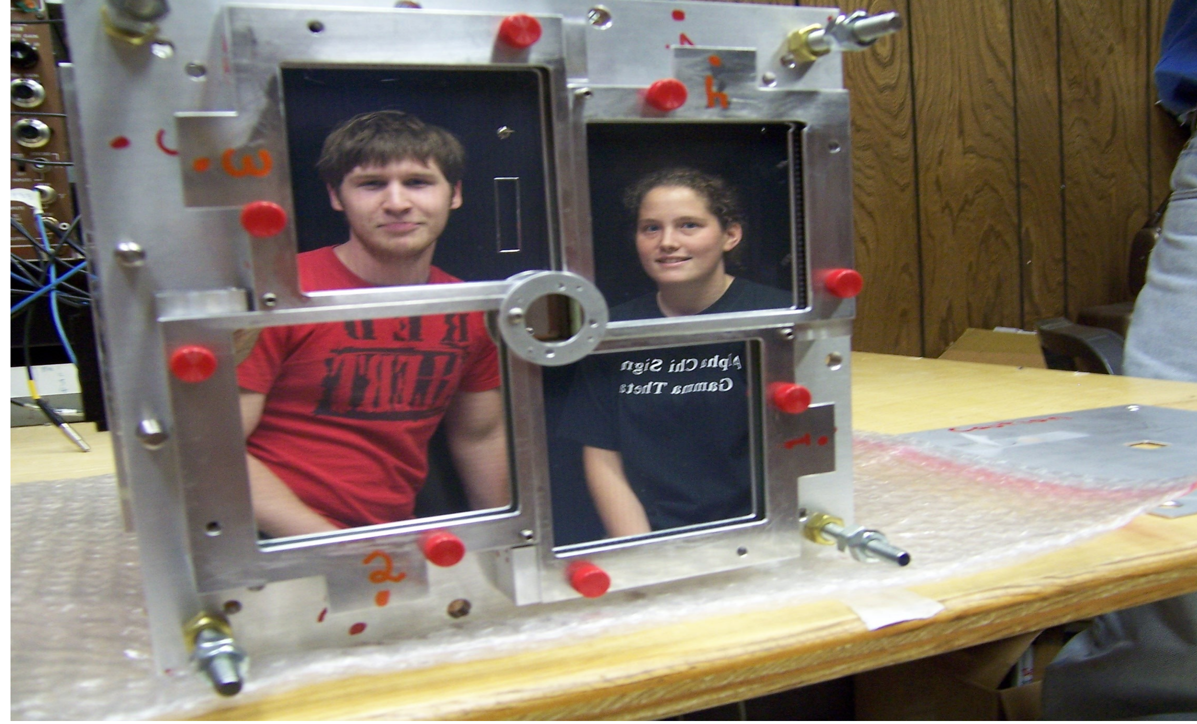




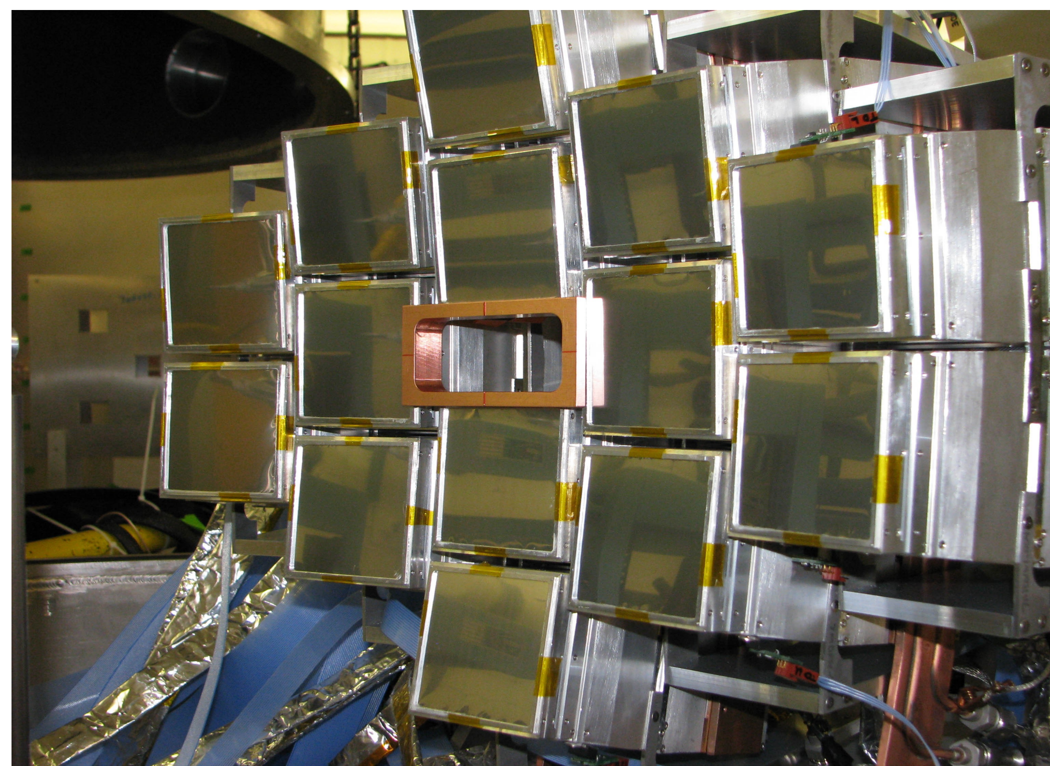
Soft dipole in ^{6}He

Nakayama PRL 85 (2000)262
Nakamura Eur. Phys. J. A 12 (2002) 33

HiRA array
Washington University
Michigan State,
Western Michigan
Indiana University



Low-energy configuration
$E/A \sim 10$ MeV
ΔE–E from Si(65μ)-Si(1.5 mm)
Texas A&M University ^{10}C beam

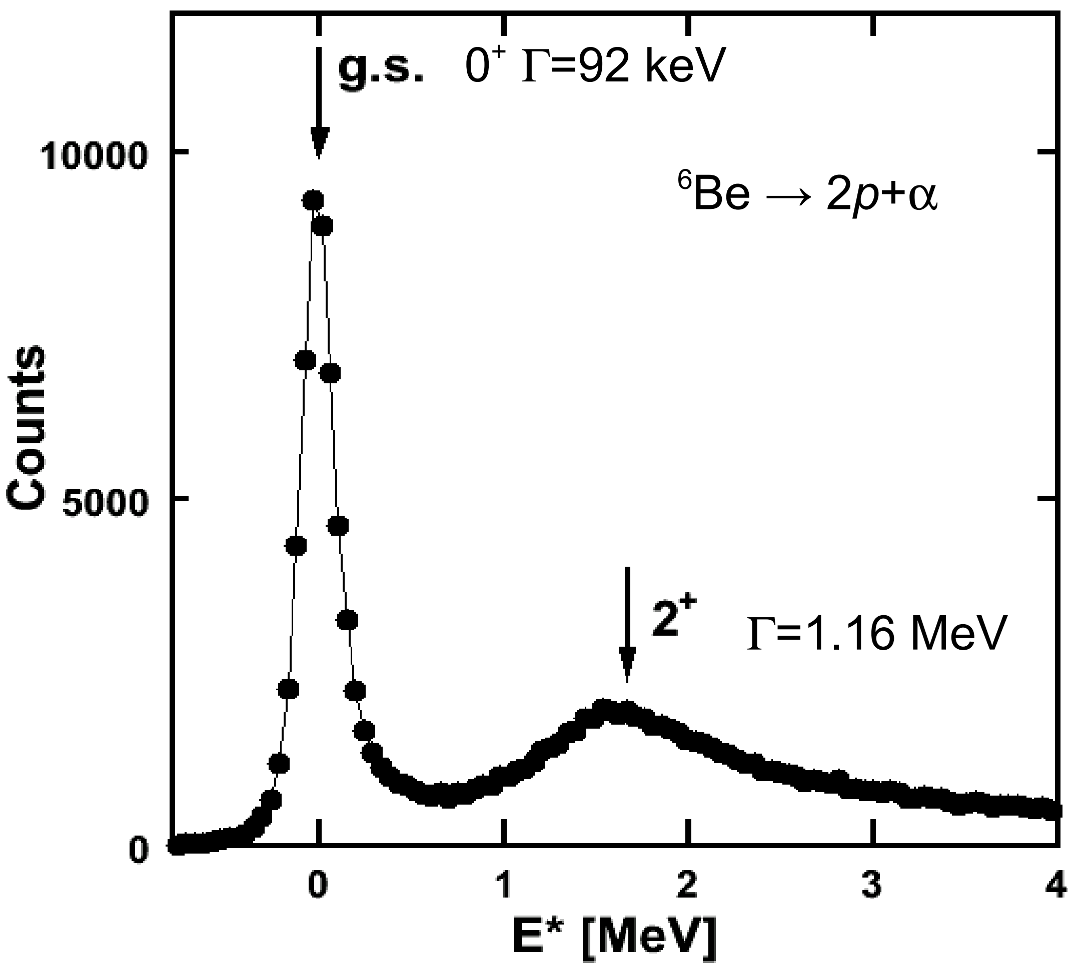


High-energy configuration
$E/A \sim 70$ MeV
E–ΔE from Si(1.5 mm)-Csi(Tl)
Michigan State University, ^{9}C, ^{12}Be beams

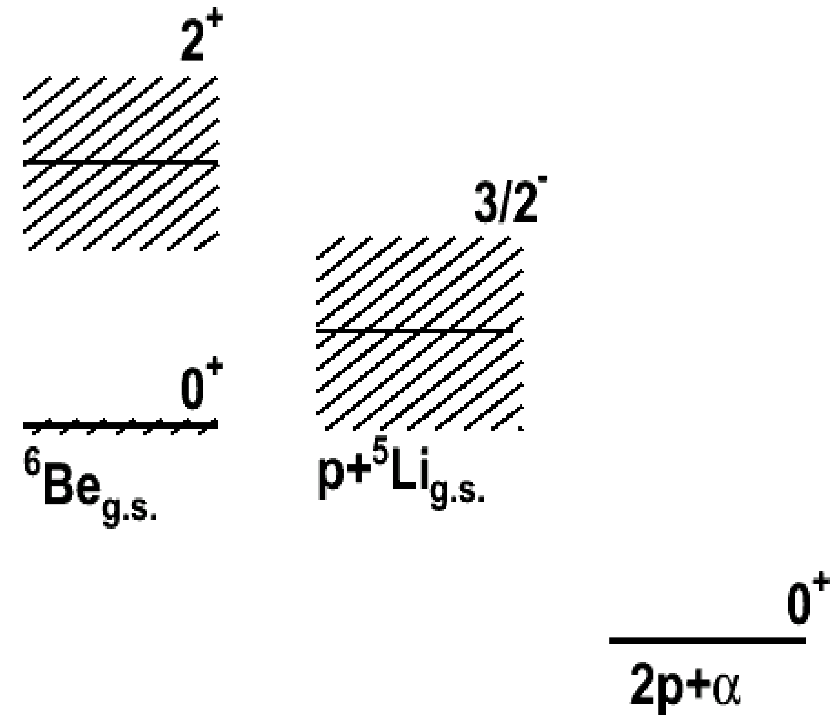
1.5 mm DSSD has 32x32 strips
~800 Si strips in experiment.
Chip readout.
Multi-hit capability

^{6}Be states

Formed by a) α decay of ^{10}C excited states (Texas A&M)
b) *n*-knockout from ^{7}Be Beam (MSU)



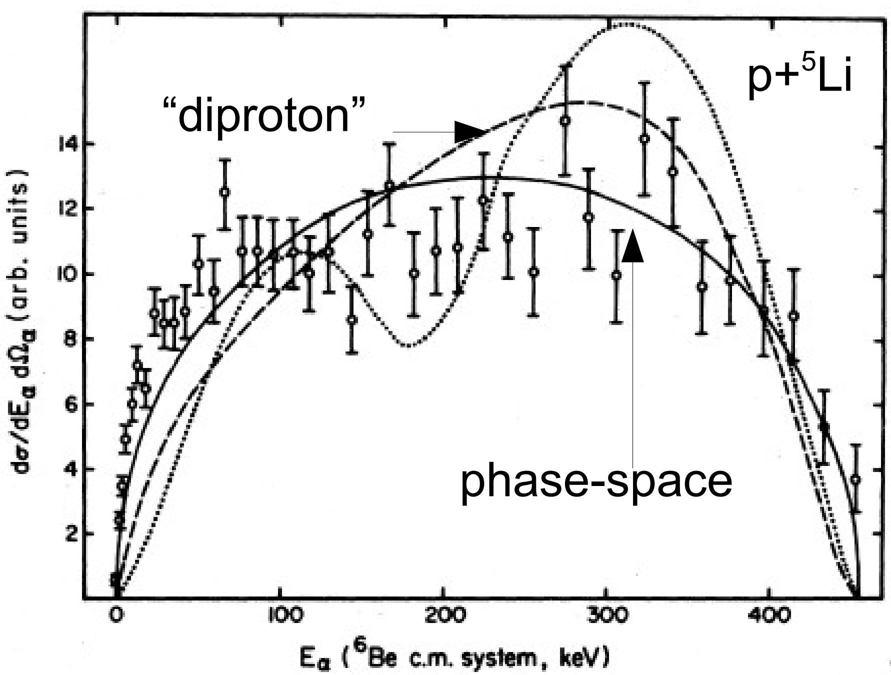
Excitation energy from invariant mass

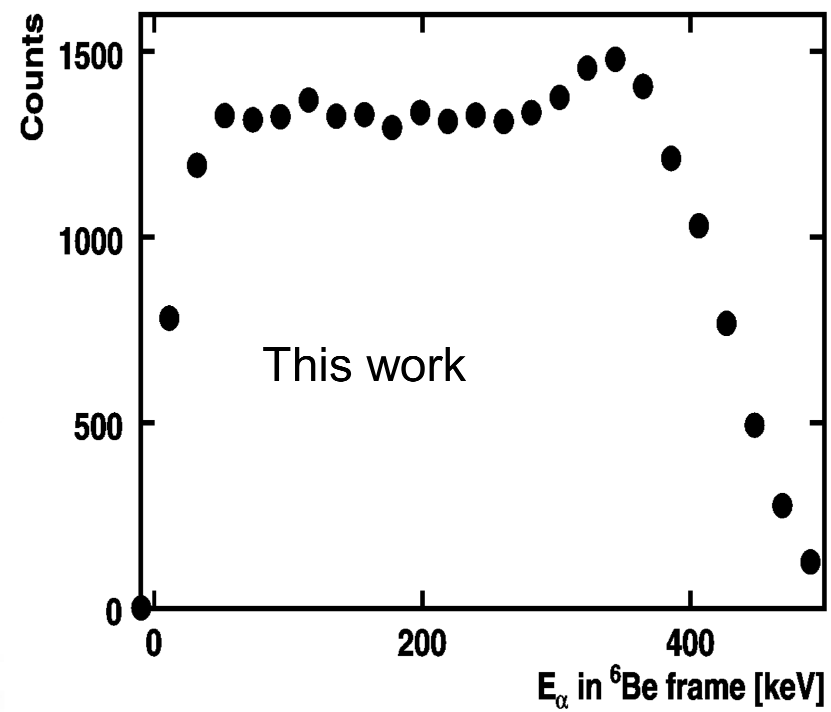


Previous experimental studies
Geesaman et al. PRC **15**, 1835 (1977)
Bochkarev et al. NPA **505**, 215 (1989)

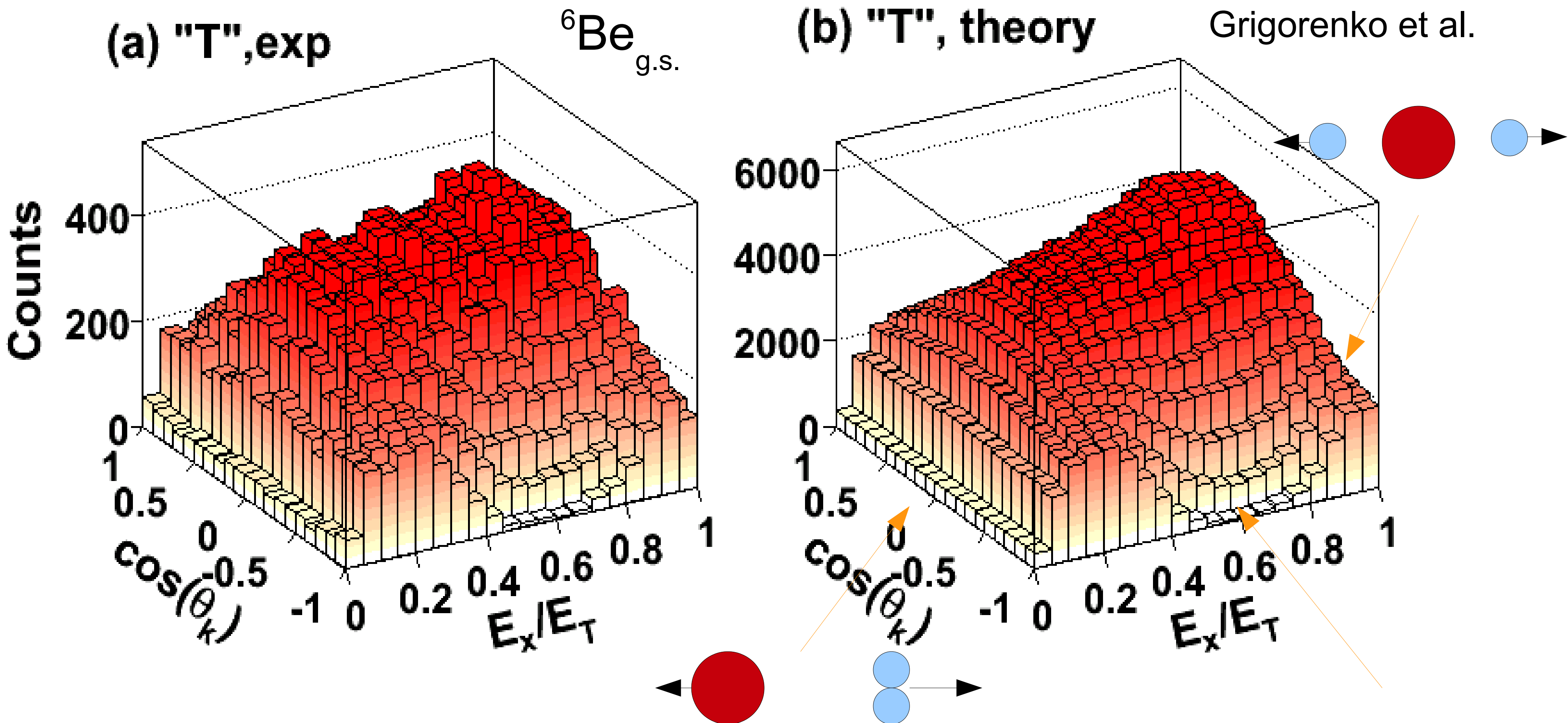
Geesaman et al. PRC 15 (1977) 1835

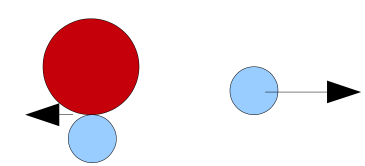
^{6}Li(^{3}He,t)^{6}Be – detect coincidence between t and α from ^{6}Be decay.





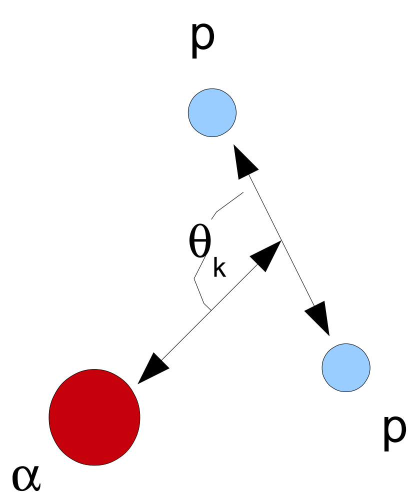
Correlations can not be described by sequential p+^{5}Li$_{g.s.}$ decay of via a diproton emission or via sampling 3-body phase space





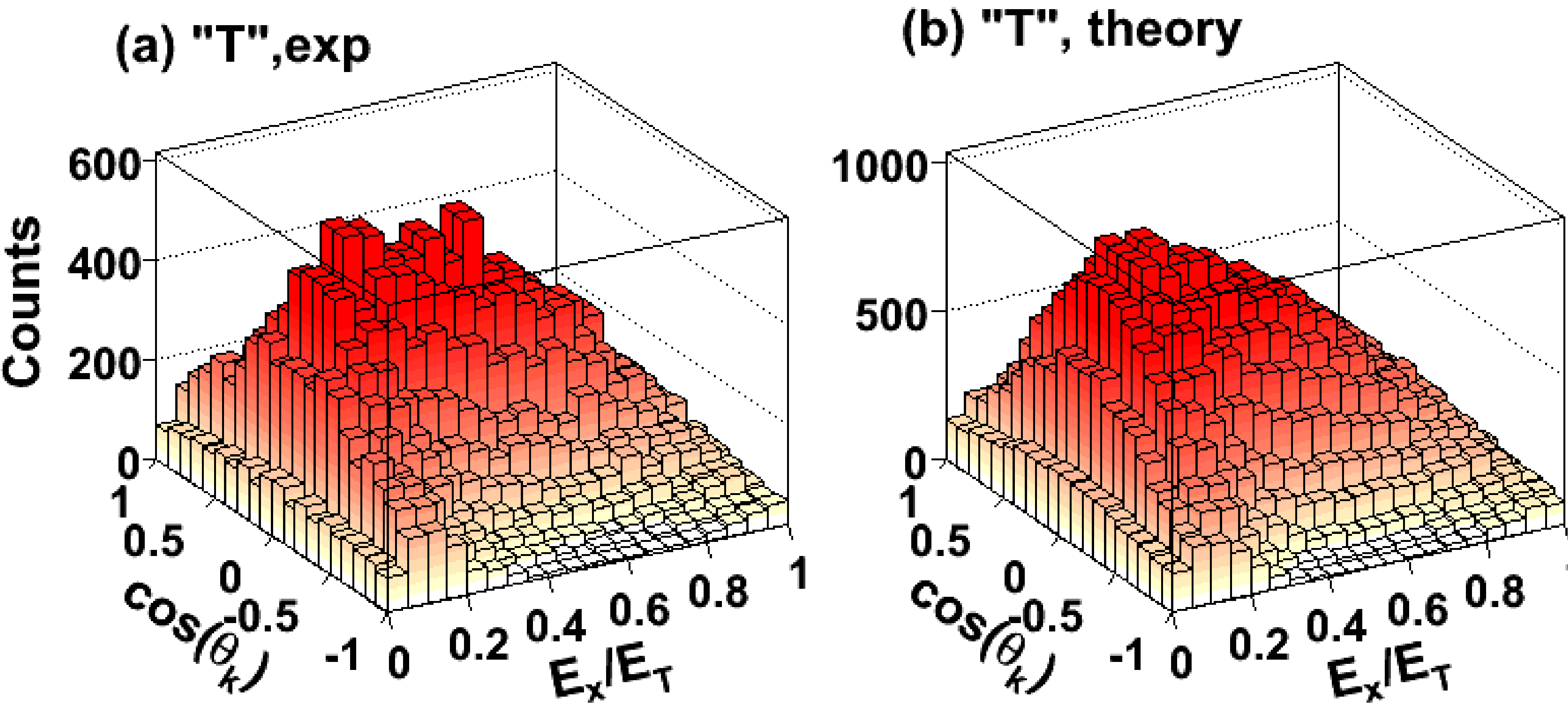
Correlations in Jacobi T system

E_x/E_T = fraction of total kinetic energy
in p-p relative motion



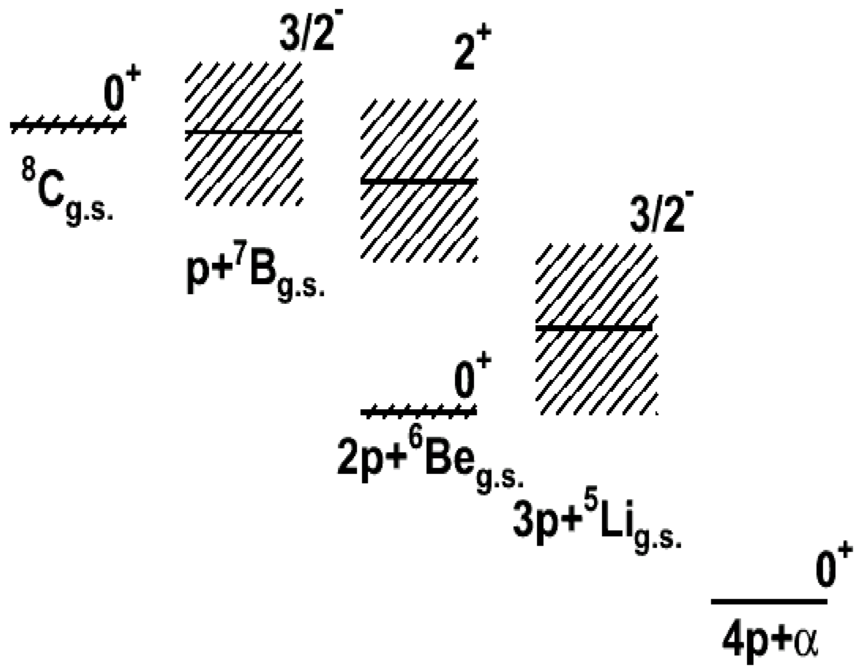
Full correlation parameter-space occupied
consistent with Grigorenko et al theory.

^{6}Be 1st excited state



Theory Preliminary

As the lifetime of this state is so short, do the correlations depend on the reaction.

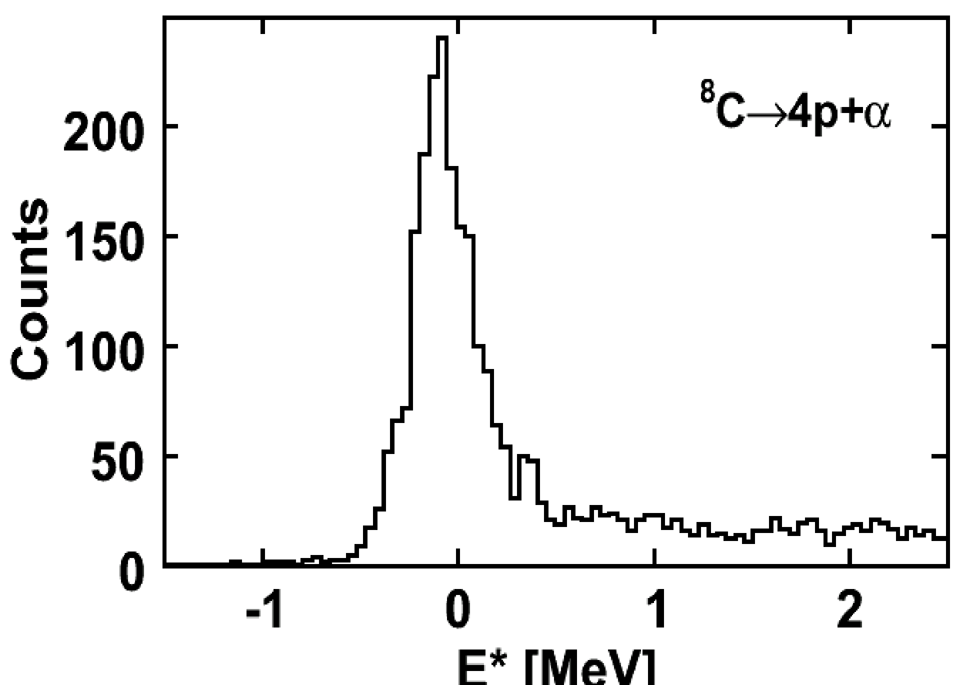


^{8}C ground state Γ=130±50 keV
Cannot be reproduced with sequential calculation (*R*-matrix) through ^{7}B.

Formed by neutron knockout
form ^{9}C beam (*E/A*=70 MeV)

Unstable to decay to 4*p*+α.

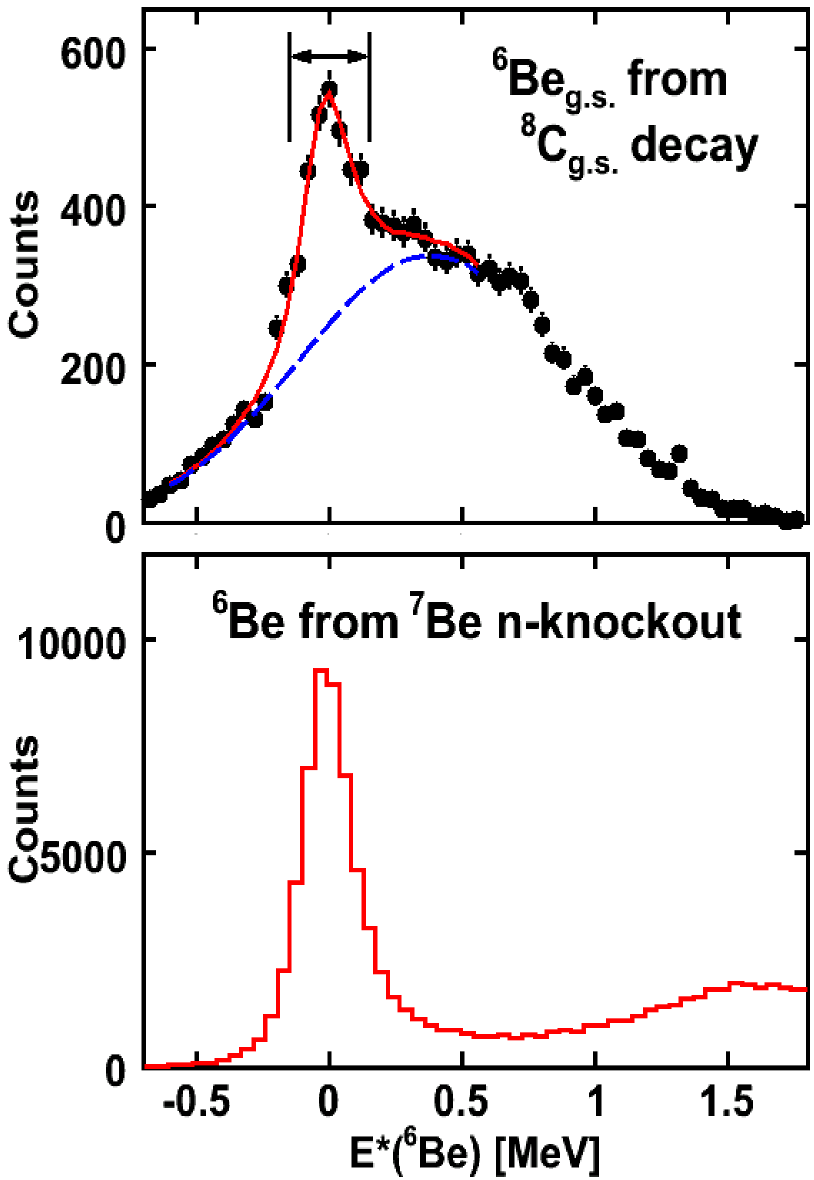
Five-body decay?
Some type of sequential decay?
Only long-lived intermediate possible is $^{6}Be_{g.s.}$



~2000 events detected
~2% efficiency

New measurement of mass excess and width.

Excitation energy from invarient mass

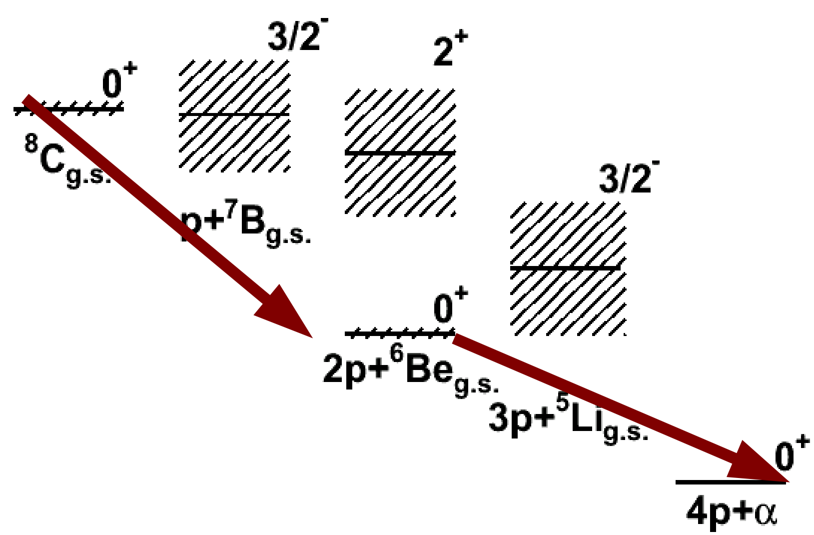


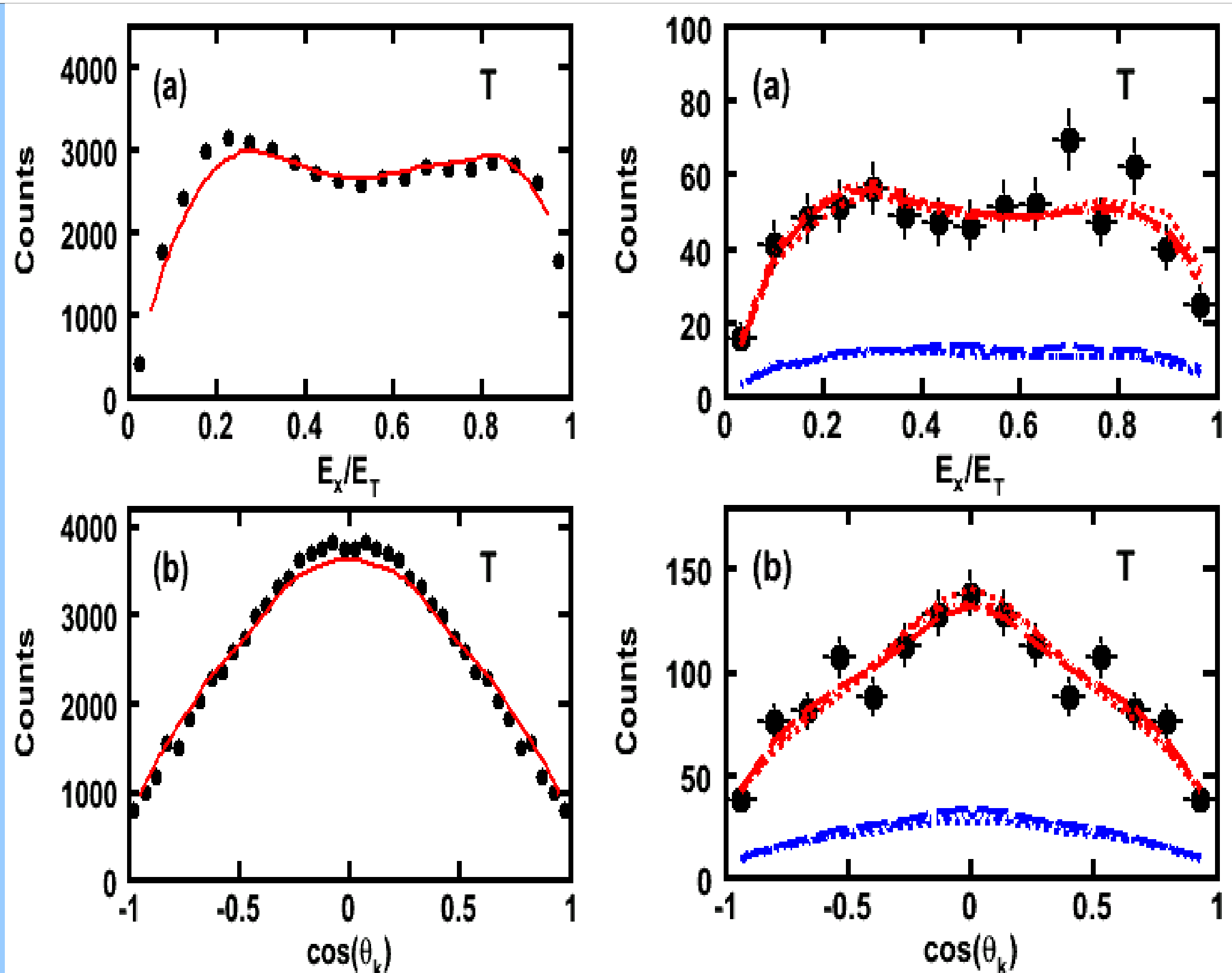
Looking for ^{6}Be in ^{8}C decay.
$^{6}Be \rightarrow 2p+\alpha$
Six possible $2p+\alpha$ subsets in each detected $4p+\alpha$ event. Histogram ^{6}Be excitation energy for each of these ways.

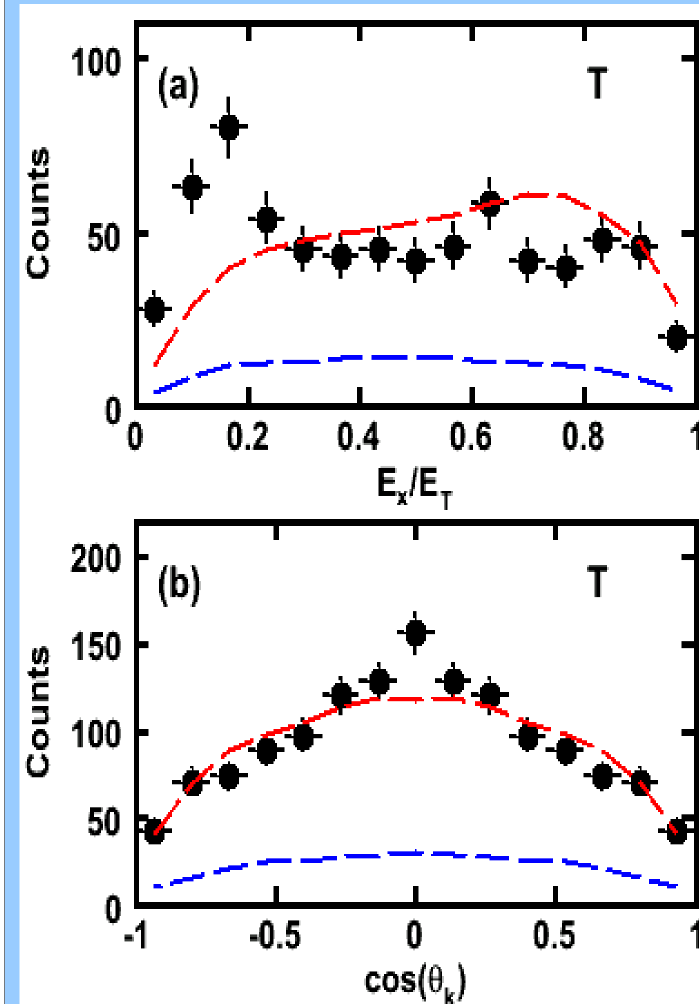
Fit $^{6}Be_{g.s.}$ peak → 1.01±0.05 $^{6}Be_{g.s.}$ fragments in each $^{8}C_{g.s.}$ event.

All $^{8}C_{g.s.}$ Fragments decay through $^{6}Be_{g.s.}$

Two sequential steps of 3-body decay.







^{6}Be decay after
^{7}Be *n*-knockout

^{6}Be decay in ^{8}C decay

Correlations in *2nd* step
of ^{8}C decay are consistent with ^{6}Be decay.

Correlations for
$^{8}C \rightarrow 2p + {}^{6}Be$
Enhancement in diproton region relative to
$^{6}Be \rightarrow 2p + \alpha$ decay.

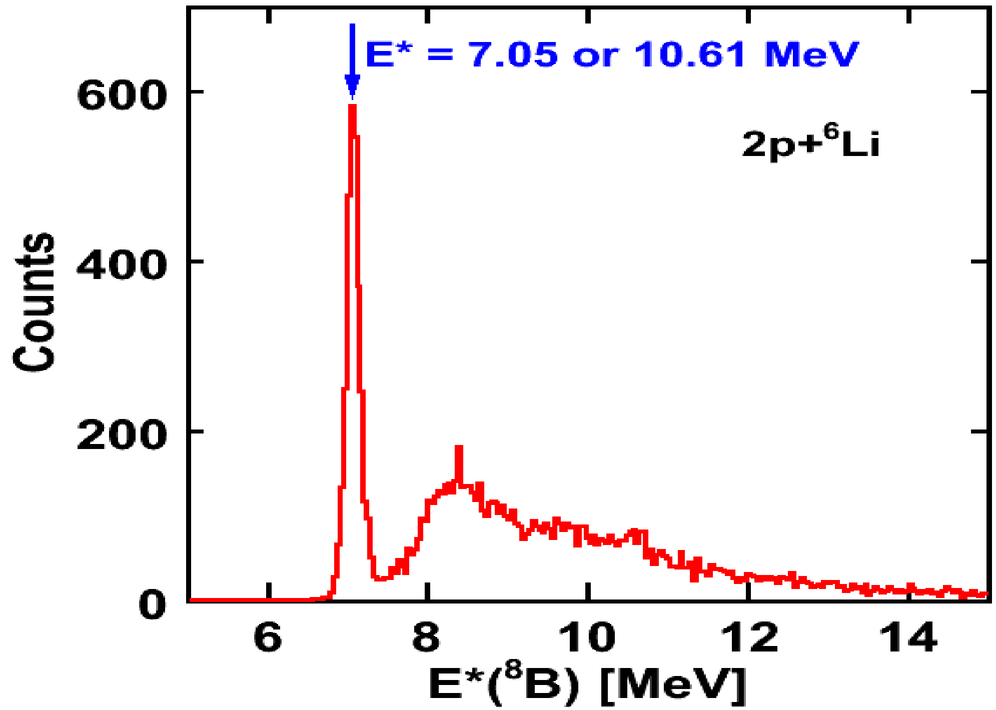
To calculate the *2p* decay of ^{8}C, does one need to consider 5-body models.

Are there other 4*p* emitters?

Maybe ^{18}Mg ($\rightarrow 2p+^{16}$Ne) $\rightarrow 4p+^{14}$O

^{21}Si ($\rightarrow 2p+^{19}$Mg) $\rightarrow 4p+^{17}$Ne

No estimates of their mass or width at the moment.
Could be produced in one or two-neutron knockout reactions



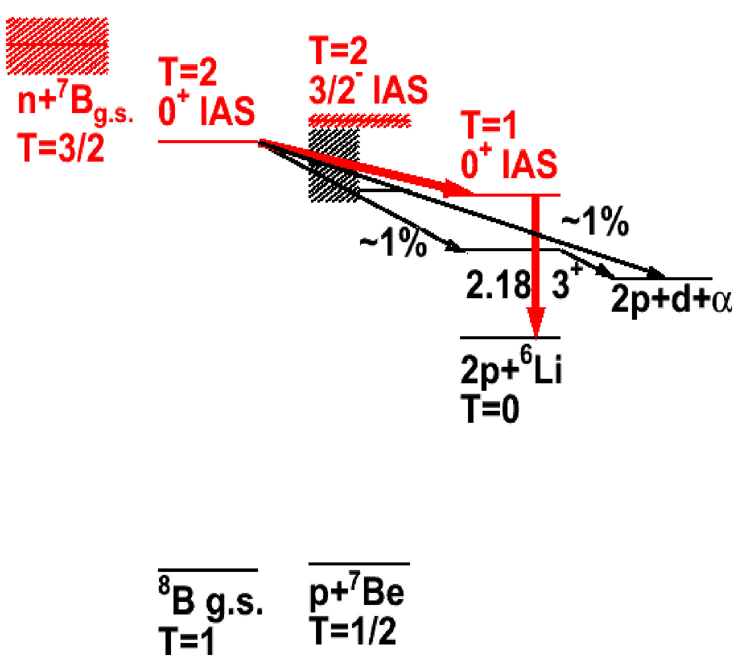
^{8}B excited state → 2*p* + ^{6}Li
Proton-knockout from ^{9}C beam (*E/A*=70 MeV)

Measured *E** = 7.05 or 10.61 MeV
Γ < 75 keV

No known narrow level at 7.05 MeV

$^{8}B_{IAS}$ E*=10.619±0.009 MeV, Γ<60 keV

2*p* decay from IAS to IAS



$^{8}B_{IAS}$ → 2*p* + $^{6}Li_{IAS}$

Analog states

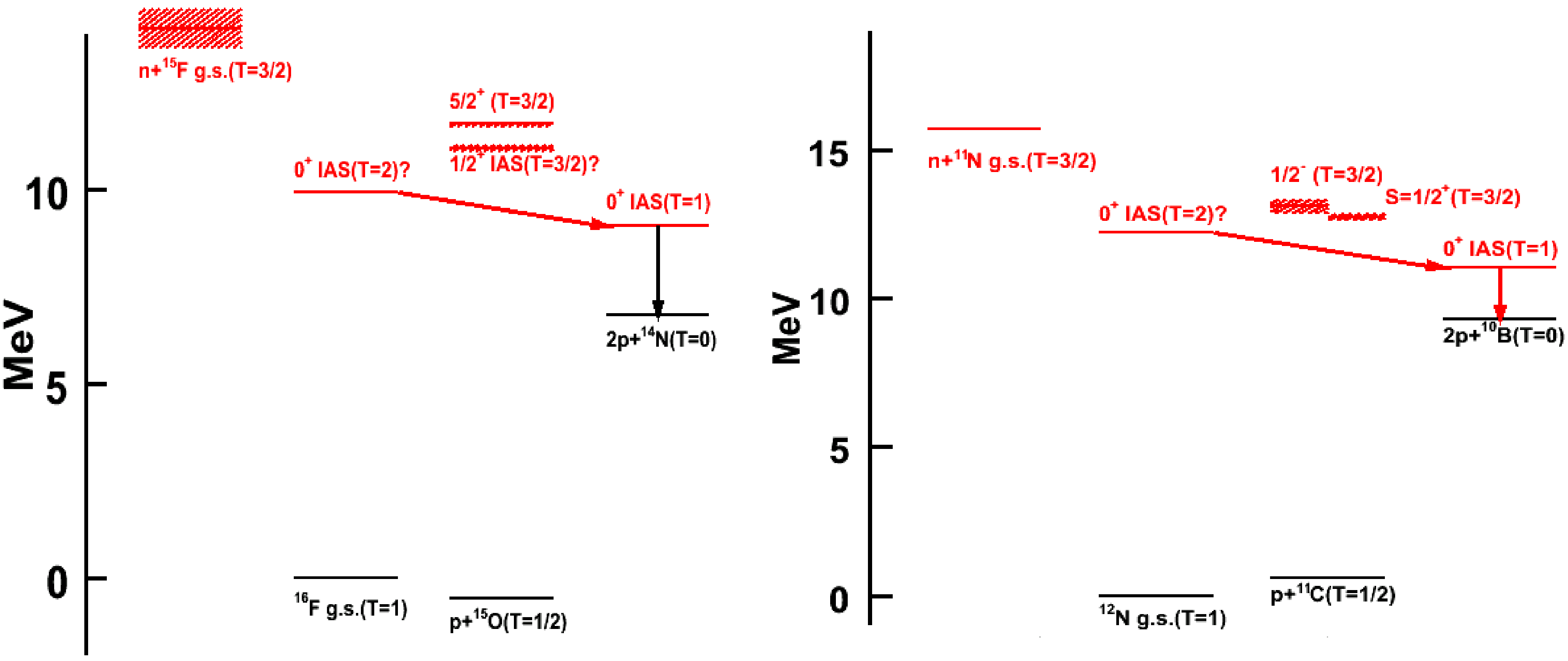
$^{8}C_{g.s.}$ → 2*p* + $^{6}Be_{g.s.}$

The two proton decay of $^{8}B_{IAS}$ is the only isospin-allowed decay mode possible.

To the extent that isospin is conserved, this is a Goldansky-type 2*p* decay.

Do the correlations between the protons give information on isospin mixing?

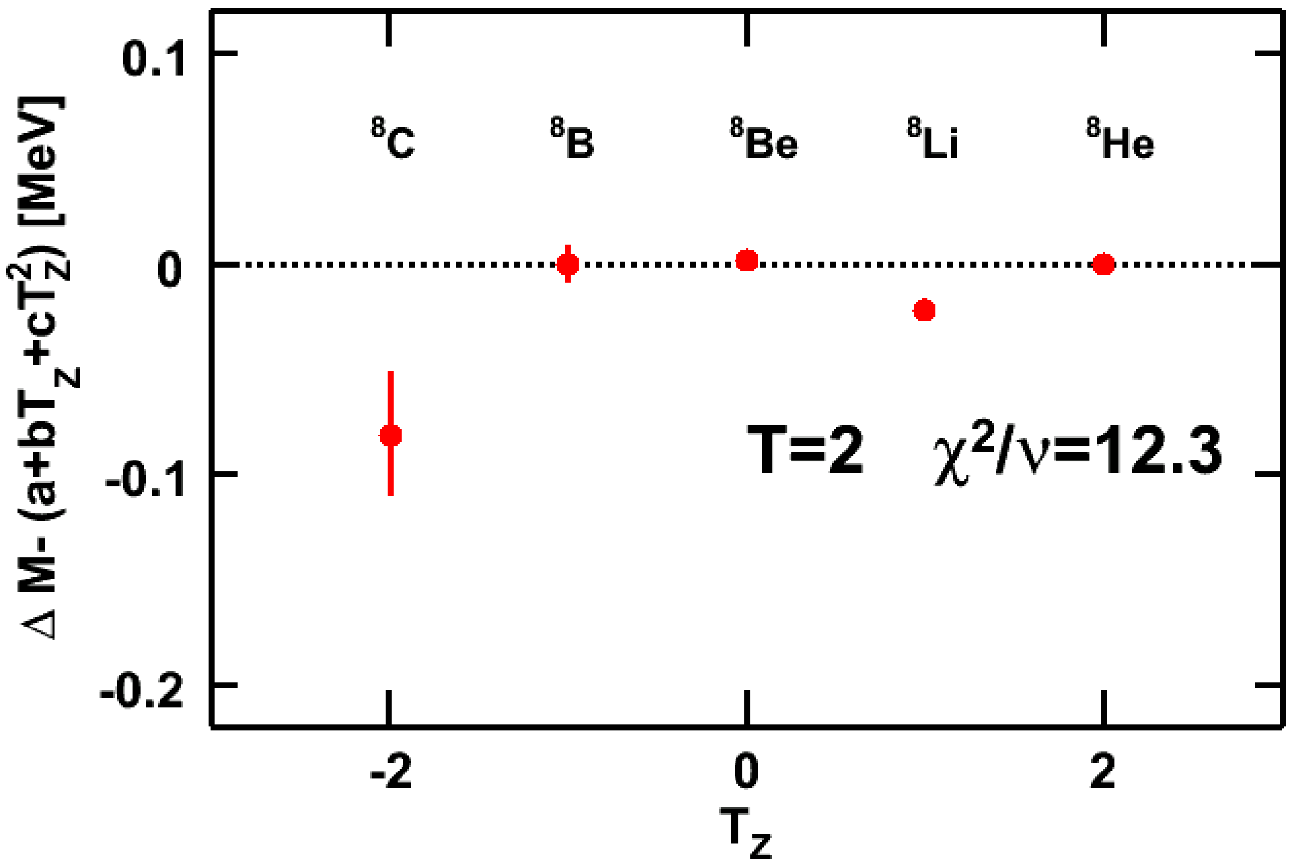
Are three other IAS to IAS 2*p* emitters?
Probably $^{12}N_{IAS}$ and $^{16}F_{IAS}$
These are analogs to the ^{12}O and ^{16}Ne 2*p* emitters.



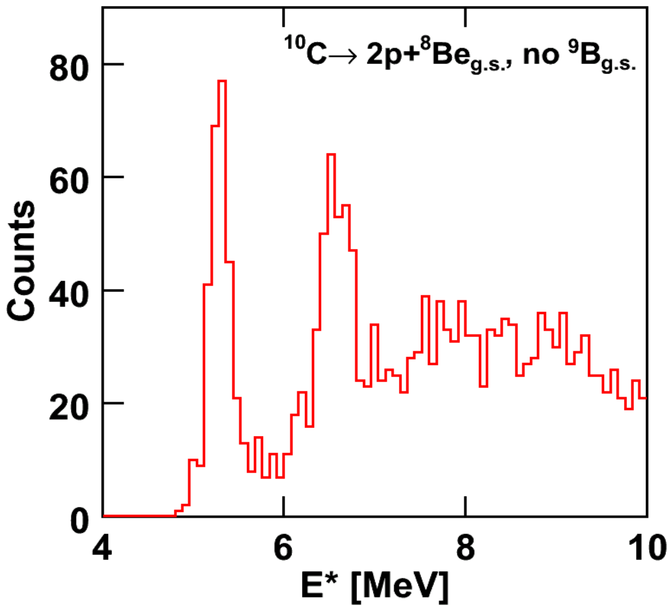
These states would complete the A=12&16 T=2 isobaric quintets.
Test of IMME equation.

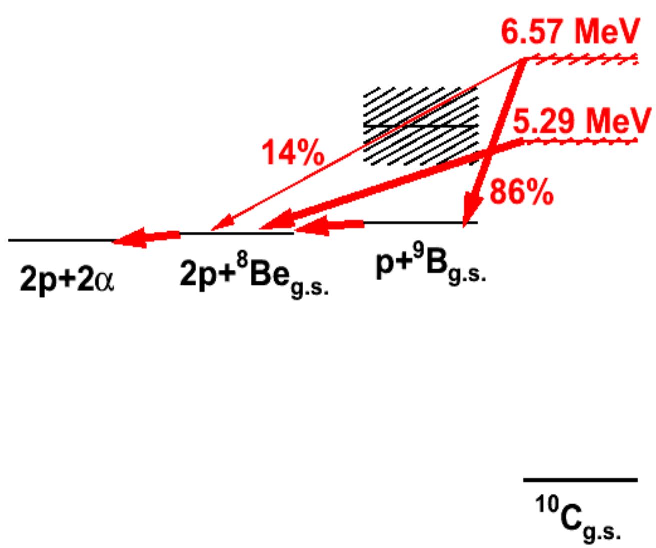
A=8 quintet - violation of the Isobaric Multiplet Mass Equation

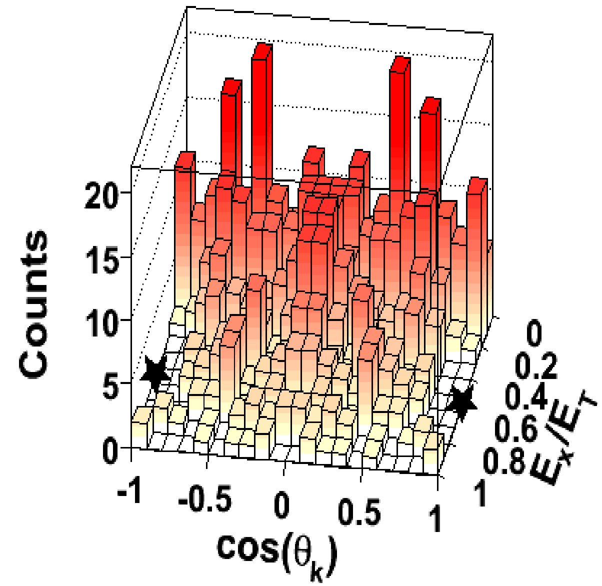
$\Delta M = a + b\,T_z + c\,T_z^2$ if isospin symmetry (Wigner)

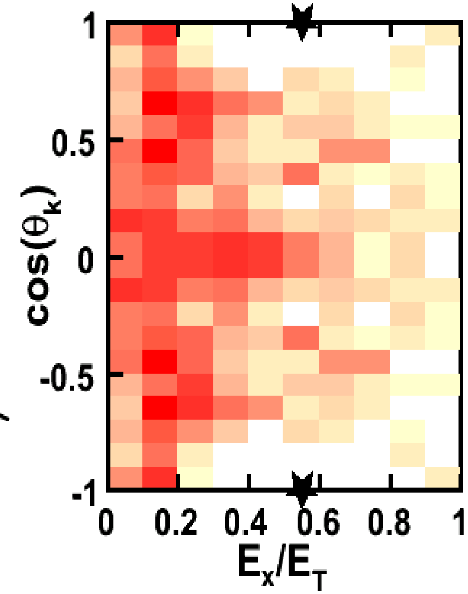


^{10}C states at 5.29 and 6.57 MeV
Populated through inelastic scattering of E/A=11 MeV ^{10}C beam





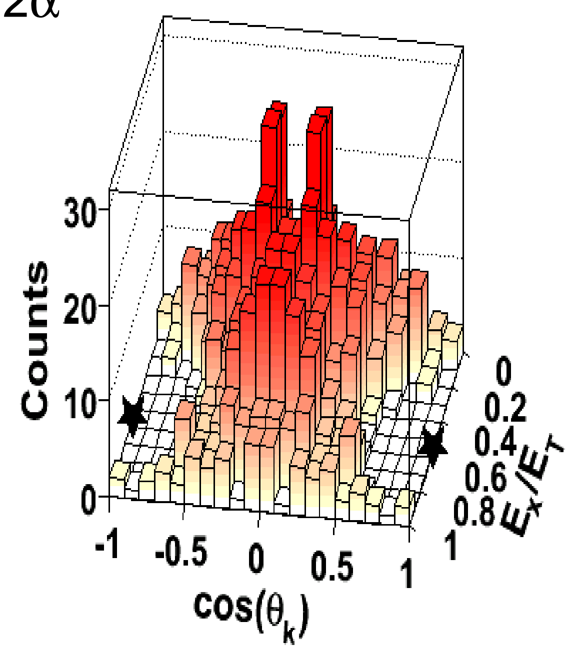


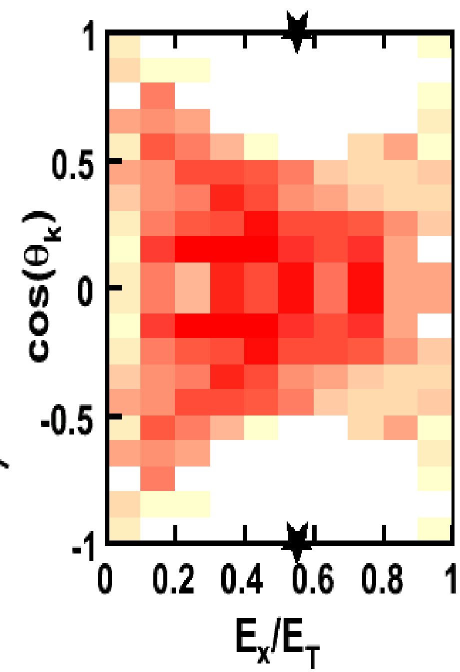


6.57 MeV

Strongly diproton-like

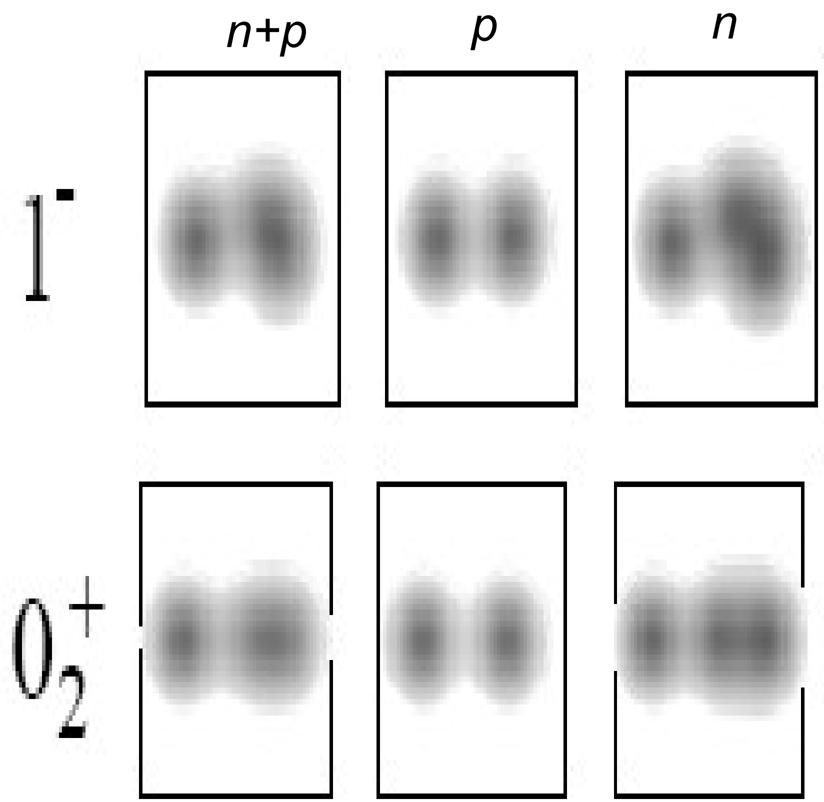
$^{10}C \rightarrow 2p+2\alpha$





5.29 MeV

These states are expected to have strong 2-α cluster structure.



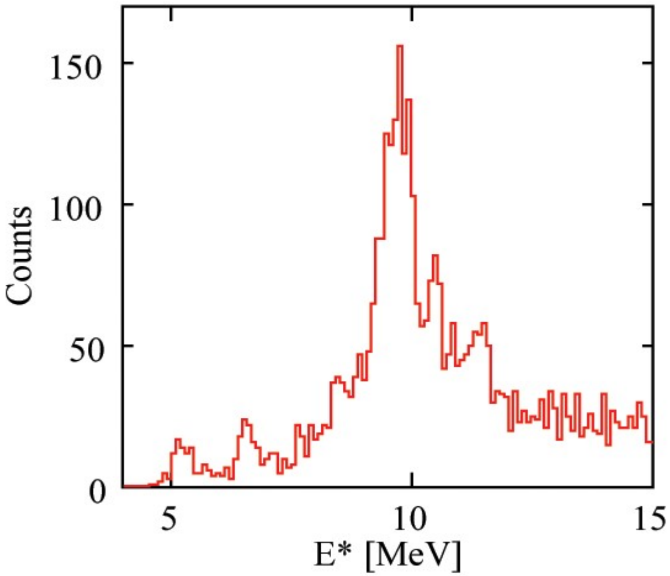
AMD density predictions
For mirror nucleus ^{10}Be

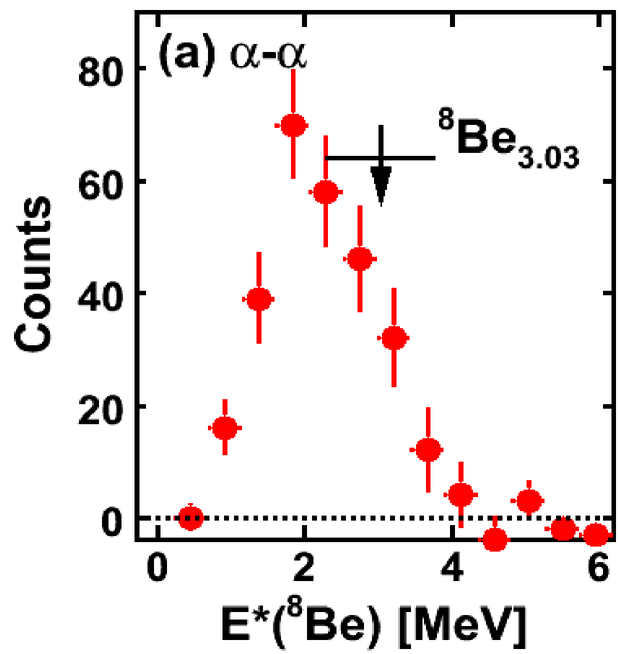
These ^{10}C excited state should have strong cluster structure,
Either 1^- and 0^+ states or members of rotational bands built on these states.

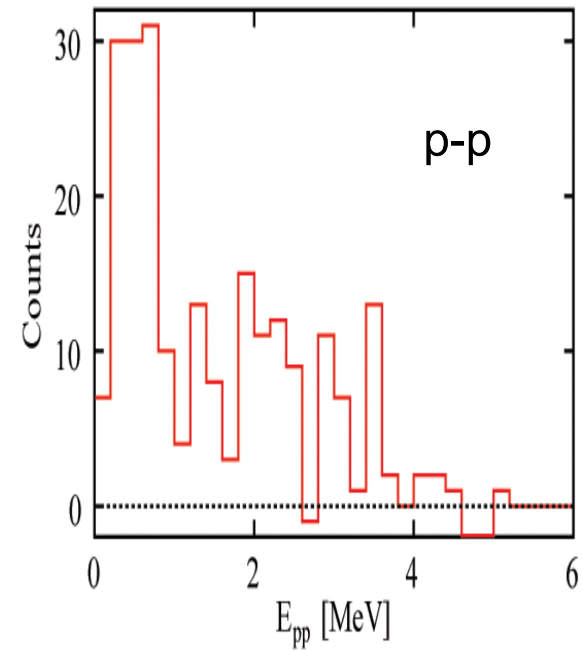
How does this cluster structure influence the *2p* decay?

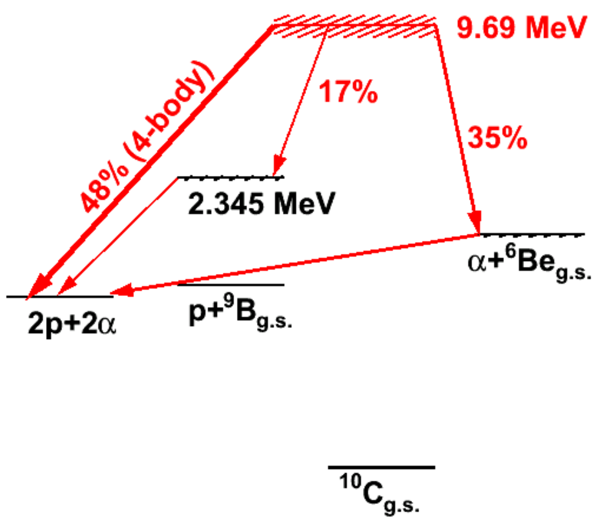
Do we need 4-body models to predict these correlations?

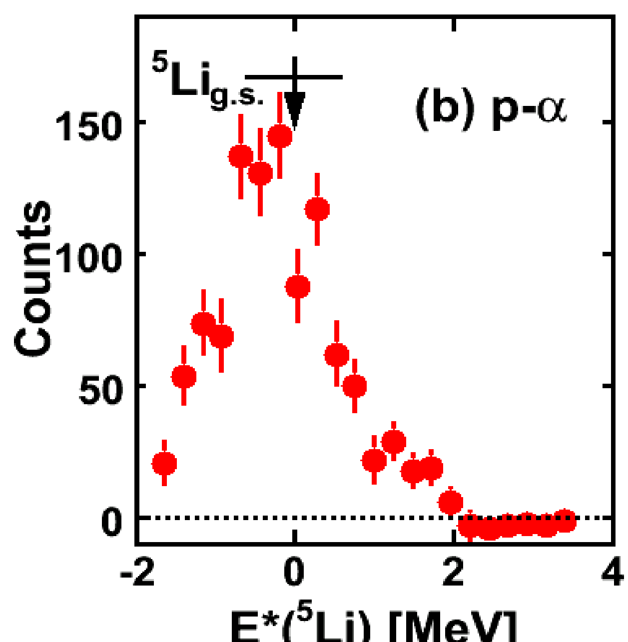
9.69-MeV state in ^{10}C (Γ= 490 keV) → 2p+2α
Formed in neutron-pickup by E/A=70 MeV ^{9}C beam

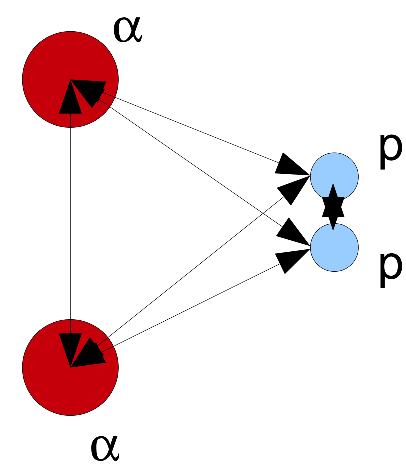












4-body decay

Large diproton strength

4 simultaneous ^{5}Li resonances?

Conclusions from experiment

1) $^{6}Be \rightarrow 2p + \alpha$ - agreement with Grigorenko theory.
2) $^{8}C_{g.s.}$ – decays by two steps of 2*p* decay. 1st step have enhanced diproton character.
3) $^{8}B_{IAS} \rightarrow 2p + {}^{6}Li_{IAS}$ Goldansky type decay if isospin is conserved.
4) $^{10}C^{*} \rightarrow 2p+{}^{8}Be_{g.s.}$ Strong diproton character for 6.57 MeV level. Role of a cluster structure?
5) $^{10}C^{*} \rightarrow 2p+2\alpha$ Four-body decay with enhanced diproton contribution.

PRC 82 (2010)041304(R)
PRC 80 (2009)024306
PRC 80 (2009)034602
Phys.Lett. B 677(2009) 30

Collaborators
Elson, Manfredi, Shane, Sobotka, Wiser, Mercurio, *Washington University*
Brown, Chajecki, Coupland, Iwasaki, Kilburn,
Lee, Lynch, Sanetullaev, Tsang, Winkelbauer, Youngs, *Michigan State University*
Marley, Shetty, Wuosmaa, *Western Michigan University*
Banu, Trache, Tribble, *Texas A&M*
Ghosh, *Variable energy Cyclotron Centre*
Howard, *Rutgers University*
Grigorenko, Egorova, Sharov, *Dubna*
Zhukov, *Chalmers University of Technology*

Calculations

1/ Grigorenko's 3-body cluster model – works well so far. Correlations only compared to a few systems so far.
Wavefunctions calculated in hyperspherical coordinates – matched to approximate outgoing waves. Input are two-body potentials – need a three-body potential to get width and resonant energy correct.

3/ Diproton emission in *R*-matrix model with SM spectoscopic factor.
(Barker and Brown) Predicts correct decay
width for ^{6}Be,^{8}C, ^{45}Fe. Doesn't work for ^{12}O (experimental value wrong) .
However experimental correlations are not just diproton in nature.

In many cases we need to include more than 3-body (^{8}C, ^{10}C).

Isospin considerations?