Bridging two-proton emitters and neutron halos

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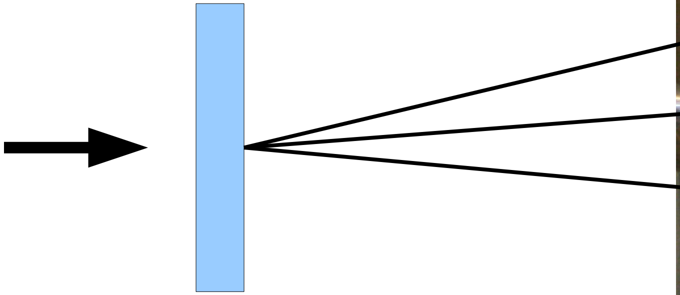
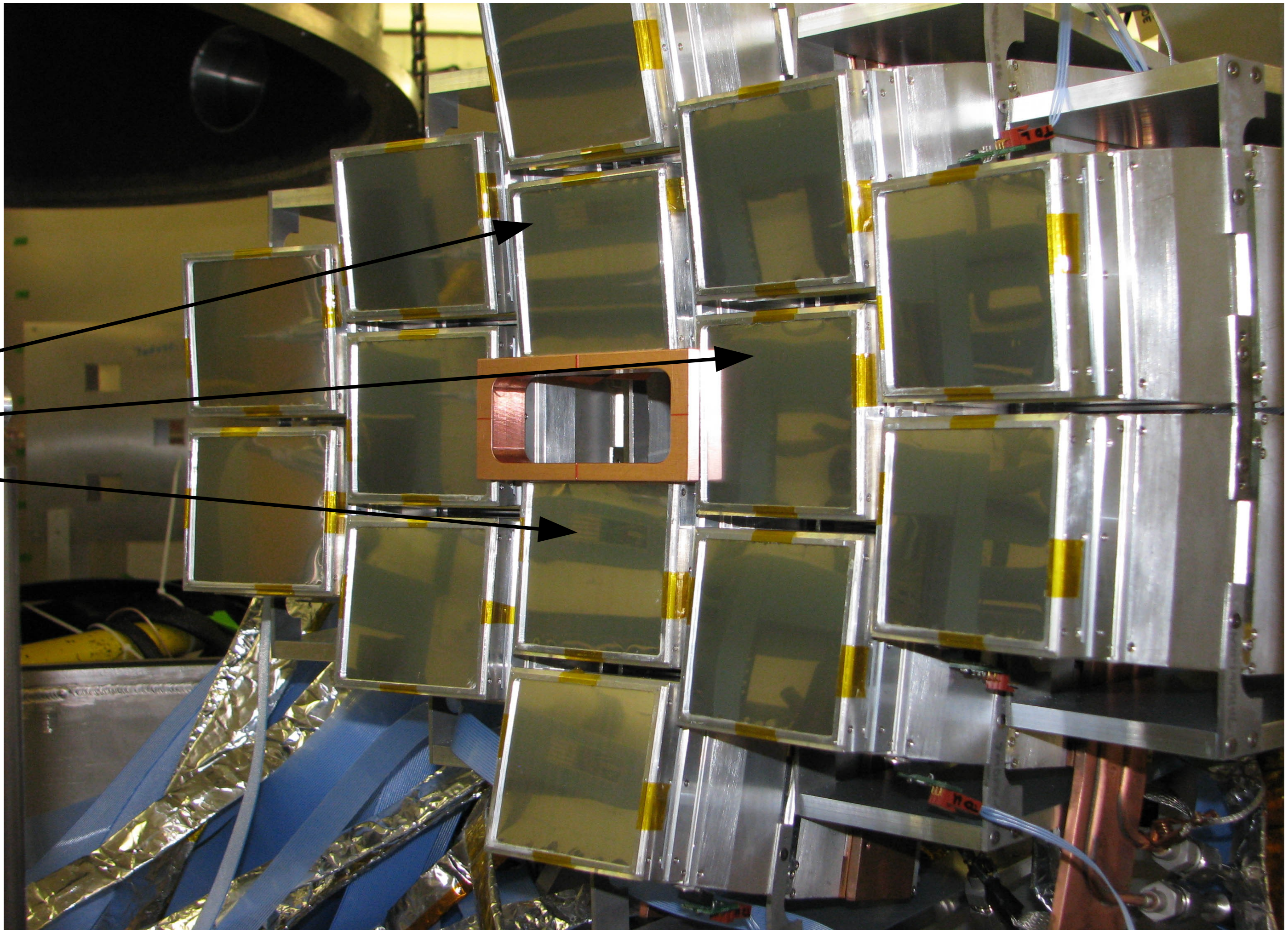
Washington University in St. Louis

High Resolution Array.

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

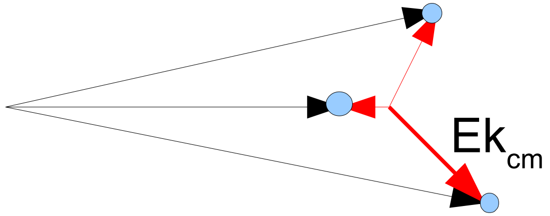




Parent nucleus decays in target.
Detect decay products in HiRA.
Need high angular resolution (Si Strips)

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

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

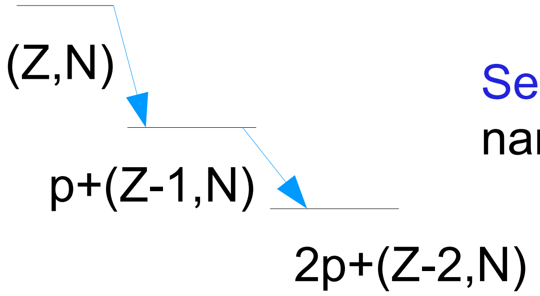
Found so far 42 resonances in ^{5,6,7}Li, ^{6,7,8}Be, ^{7,8,9}B and ^{8,9,10}C
These consist of
21 2-body exit channels
13 3-body exit channels (sequential and prompt decays)
7 4-body exit channels $2p+d+\alpha$, $p+\alpha+{}^{3}$He, $2p+2\alpha$,
1 5-body exit channels $4p+\alpha$

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).

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

Look at 2*p* decay for example

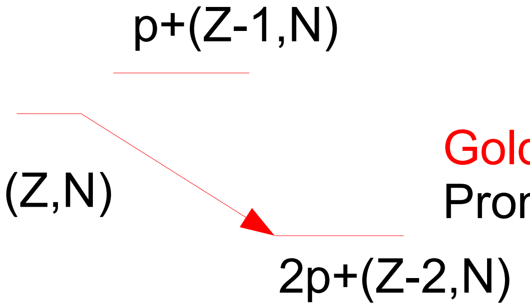


(Z,N)

p+(Z-1,N)

2p+(Z-2,N)

Sequential,
narrow intermediate state $^{10}C^*$,$^{13}O^*$, $^{17}Ne^*$, $^{16}Ne^*$

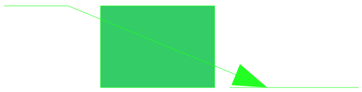


p+(Z-1,N)

(Z,N)

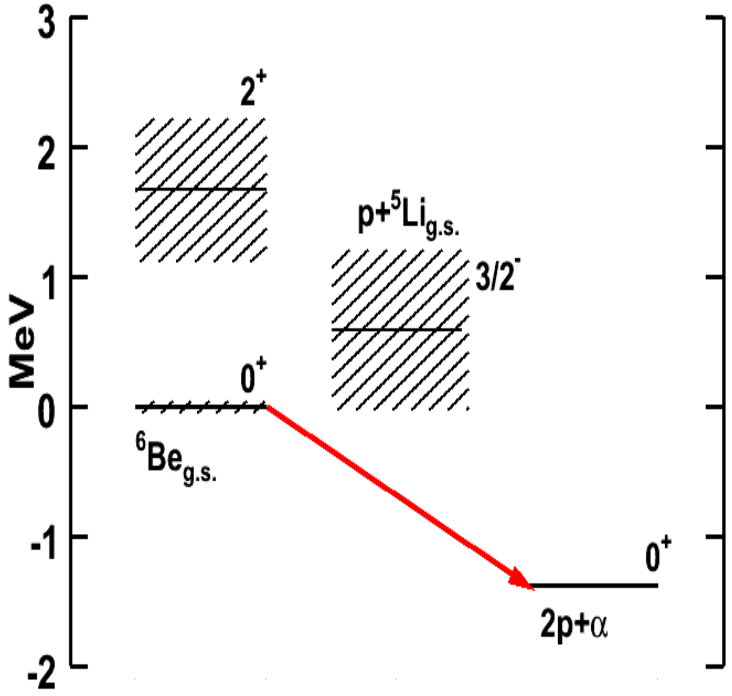
2p+(Z-2,N)

Goldansky, even Z (pairing) (^{45}Fe, ^{48}Ni)
Prompt 2*p* decay



Democratic , wide intermediate state
Lifetime too short and so must
treat as prompt 2*p* decay.
Again pairing can be important (even Z)

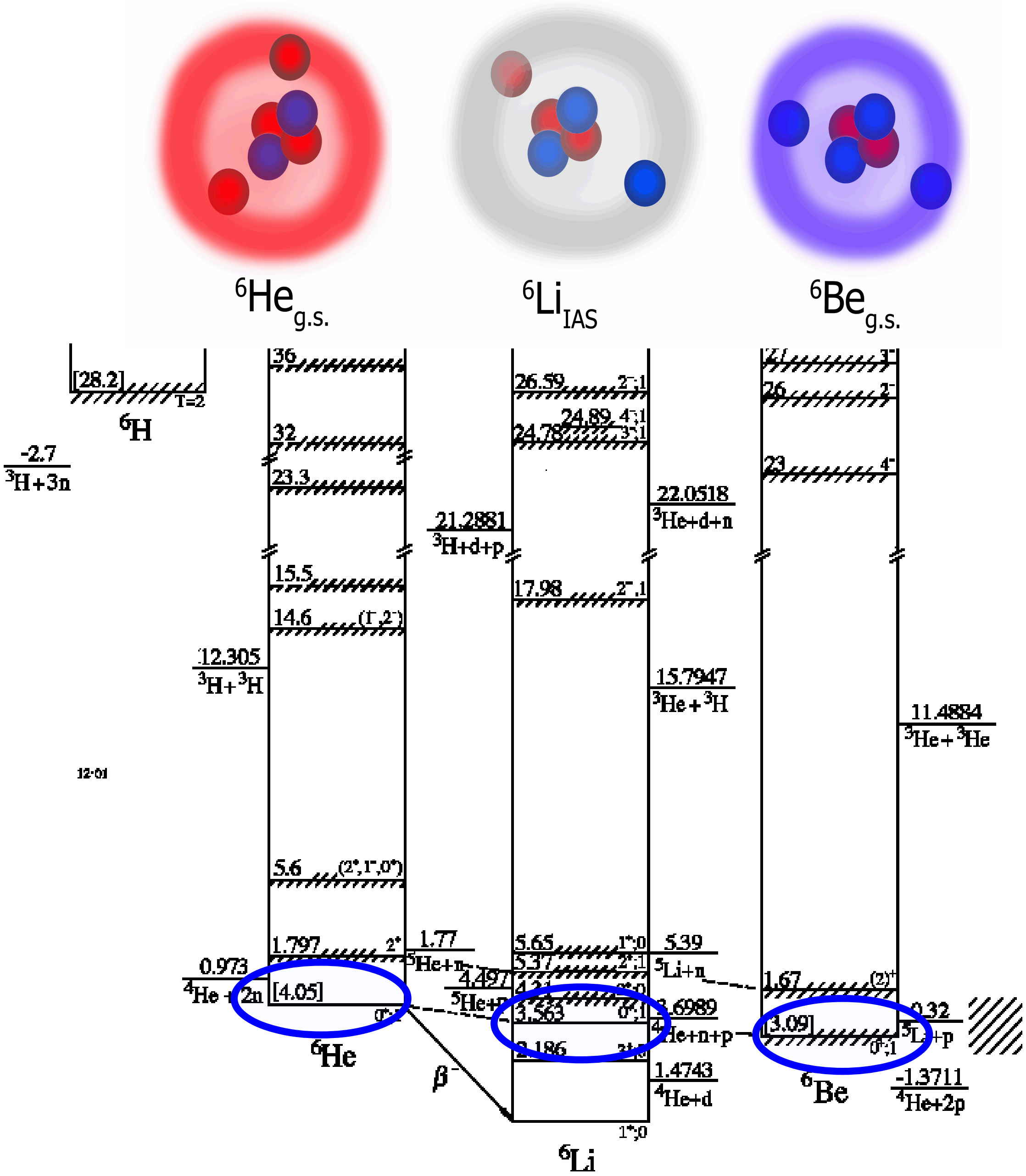
2*p* decay of light ground-state nuclei can be a combination of Goldansky and Democratic e.g. ^6Be



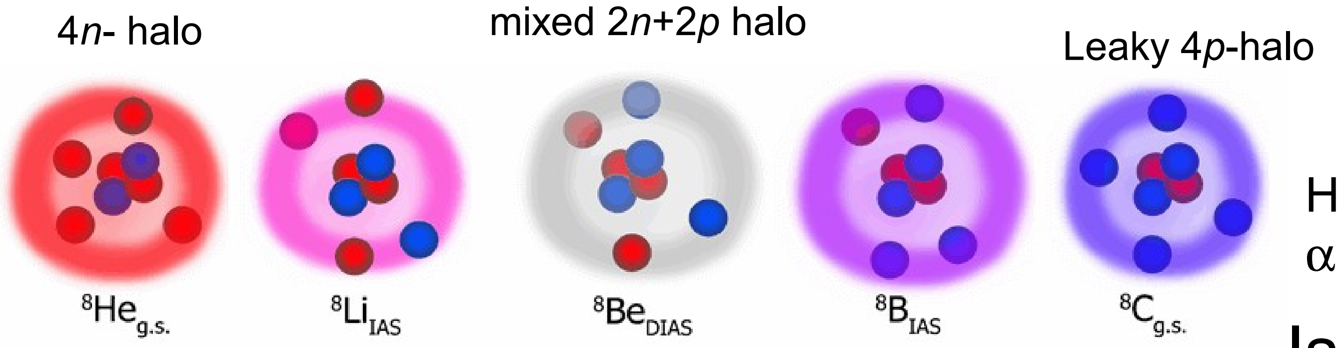
Relationship between 2*p* decay and 2*n*-halo nuclei

The lightest 2*p*-decayer $^{6}\mathrm{Be}_{gs}$ is the mirror to the 2*n*-halo system ^{6}He.
Together with ^{6}Li (IAS) form a isospin triplet with “two-nucleon halo”.

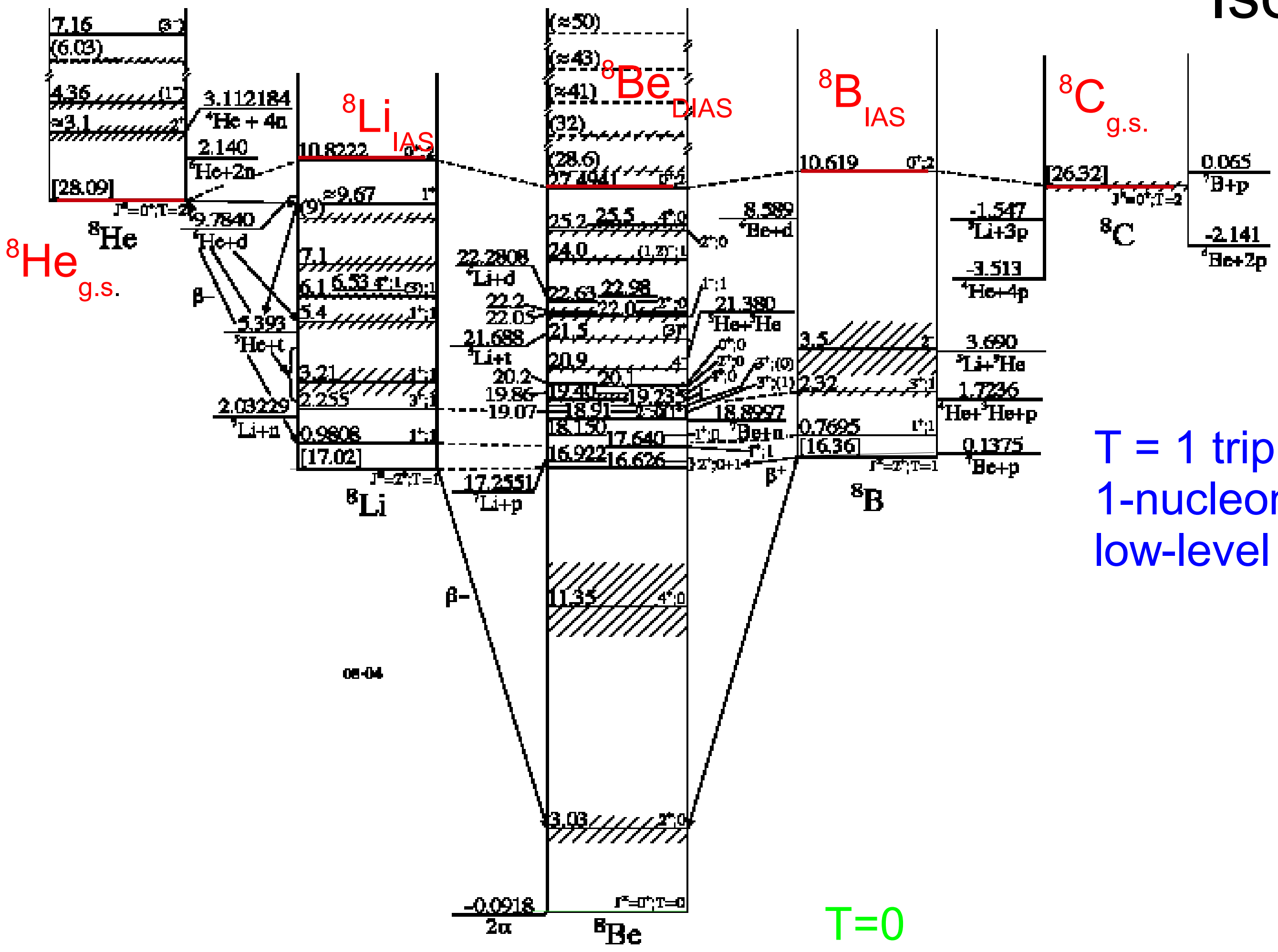
A=6 T=1 triplet
All members have a “halo structure”
n-n, n-$p_{T=1}$, and p-p pairing interactions in halo



Isobaric multiplets for A=8



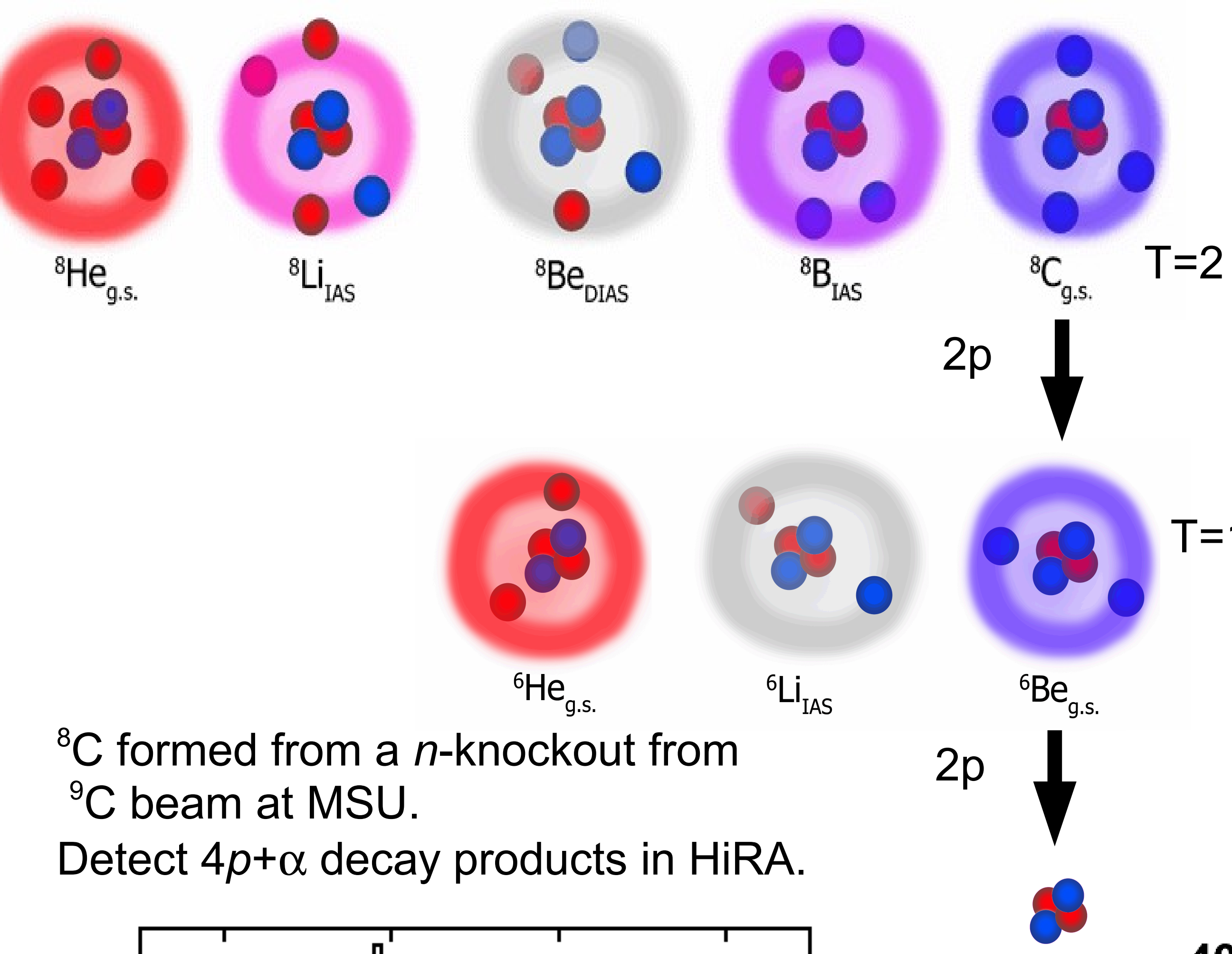
Halo structure of T=2 quintet
α core + 4-nucleon halo

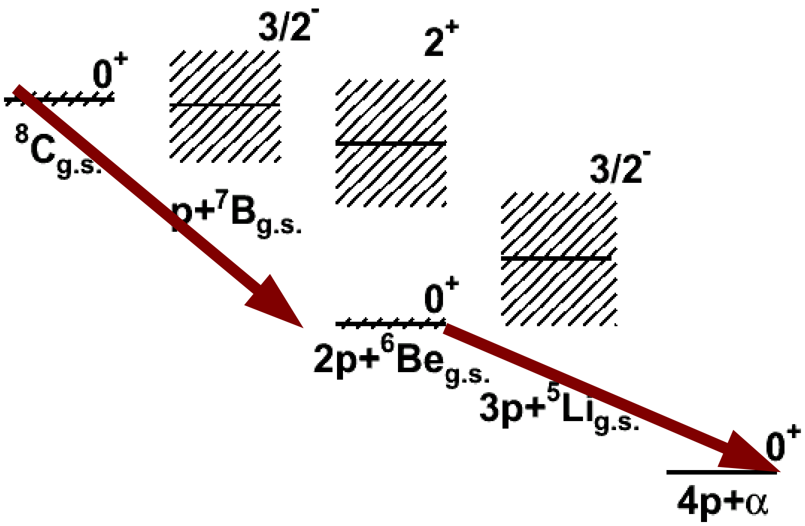


T = 2 quintet (2T+1)
4-nucleon halo
high-level bridge

T = 1 triplet
1-nucleon halo
low-level bridge

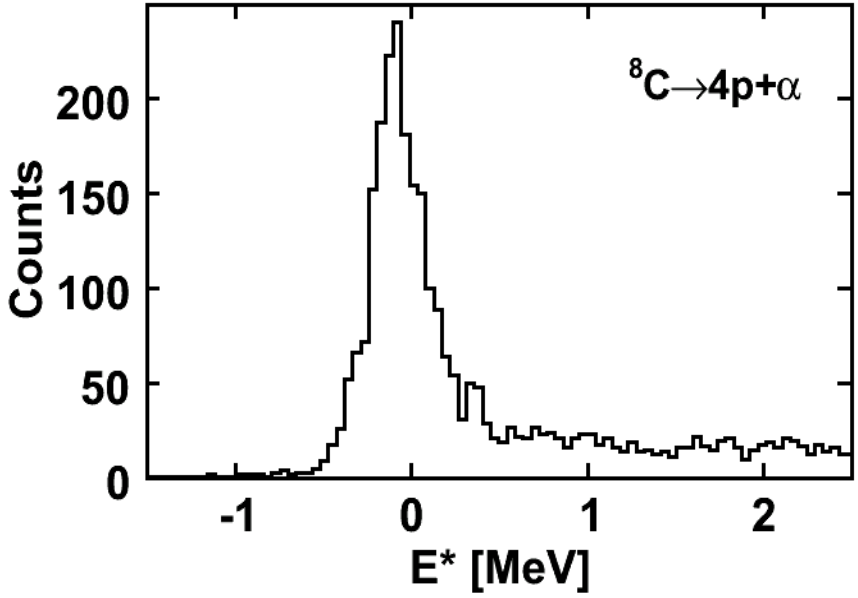
T_z=2 T_z=1 T_z=0 T_z=-1 T_z=-2



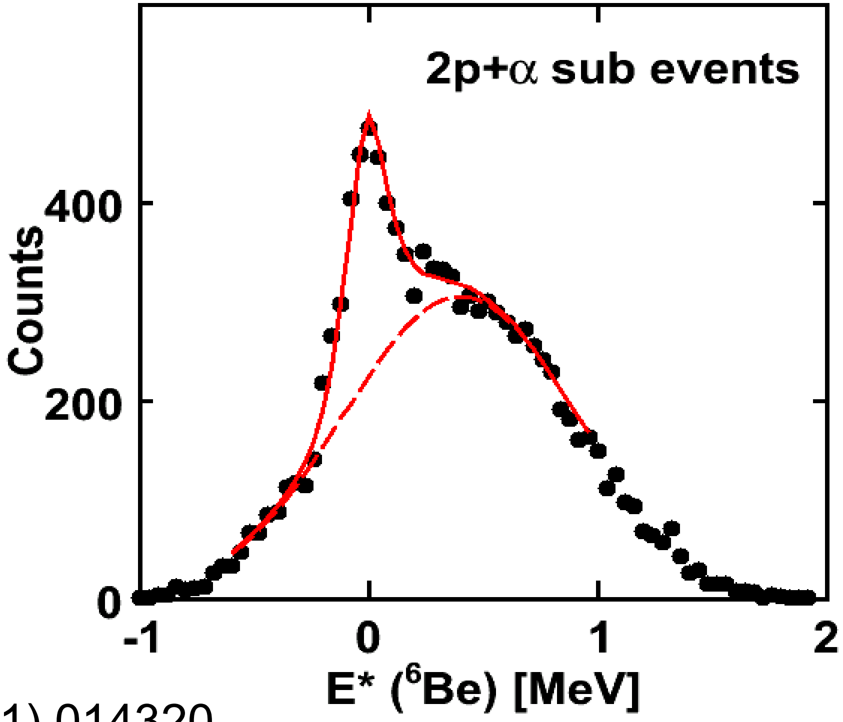


^{8}C formed from a *n*-knockout from ^{9}C beam at MSU.

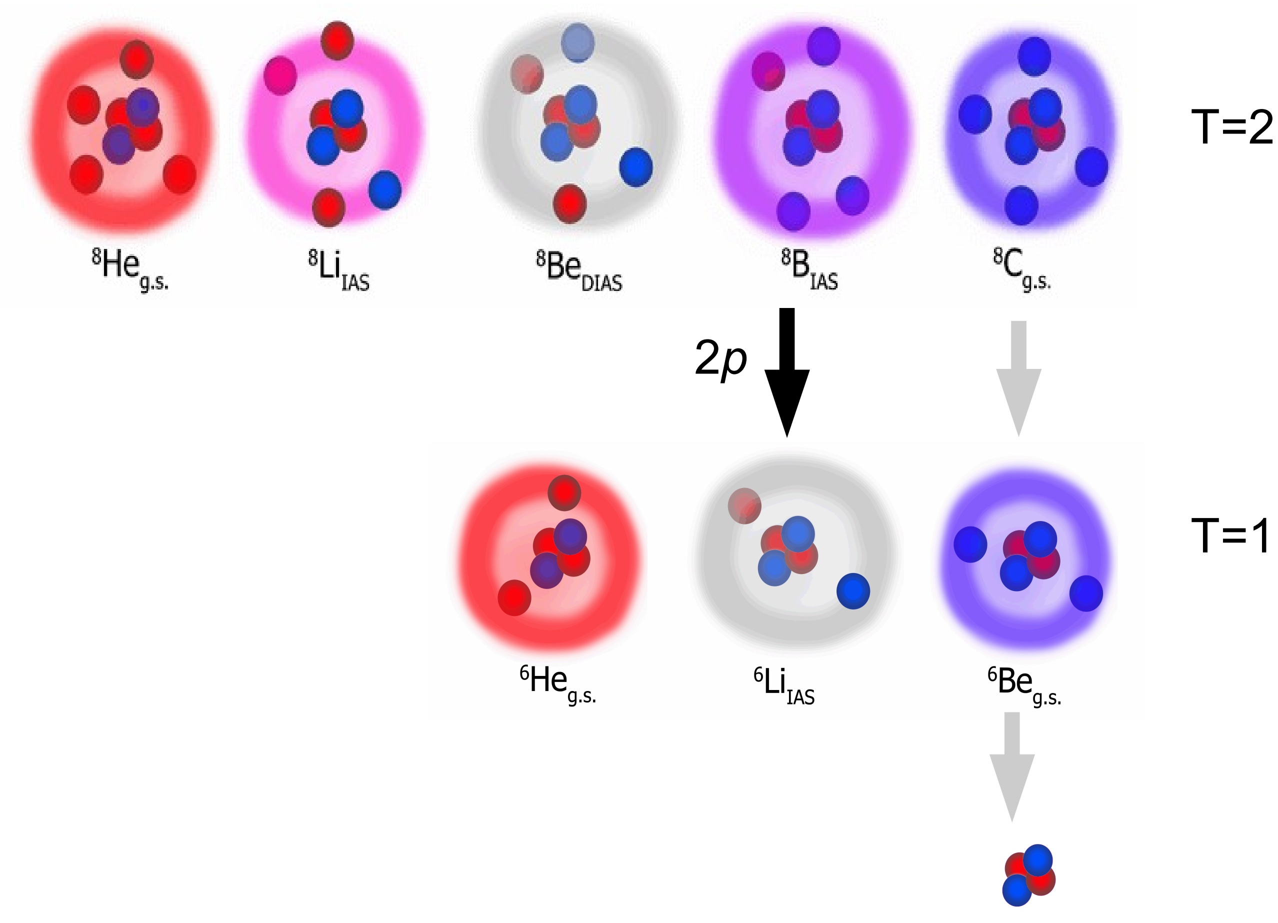
Detect 4*p*+α decay products in HiRA.

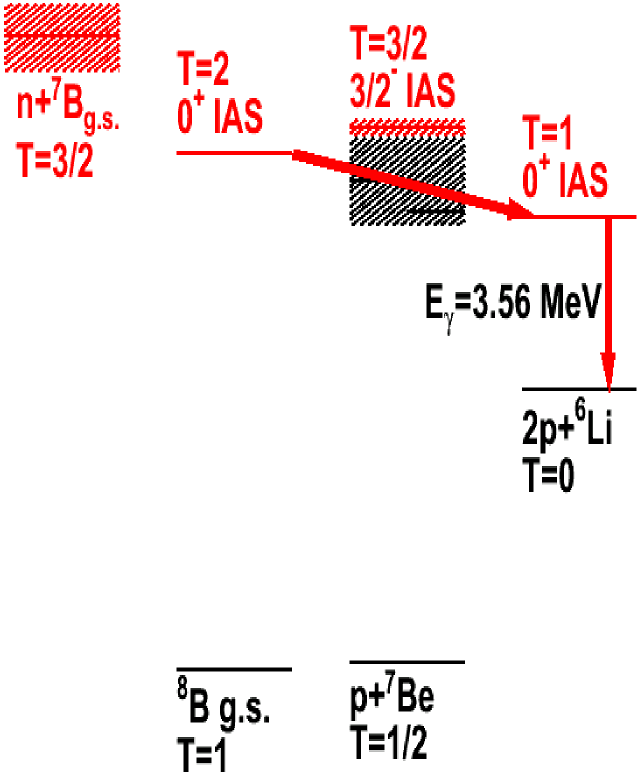


$^{8}C_{gs}$



PRC 84 (2011) 014320

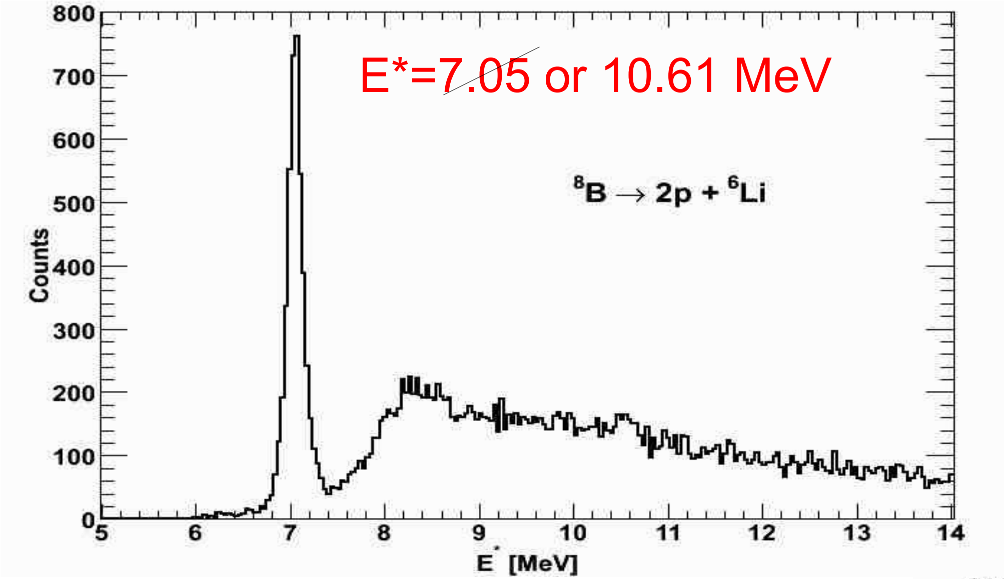




Does the isobaric analog of ^{8}C undergo prompt 2*p* decay?

An analog decay of ^{8}C$_{g.s.}$

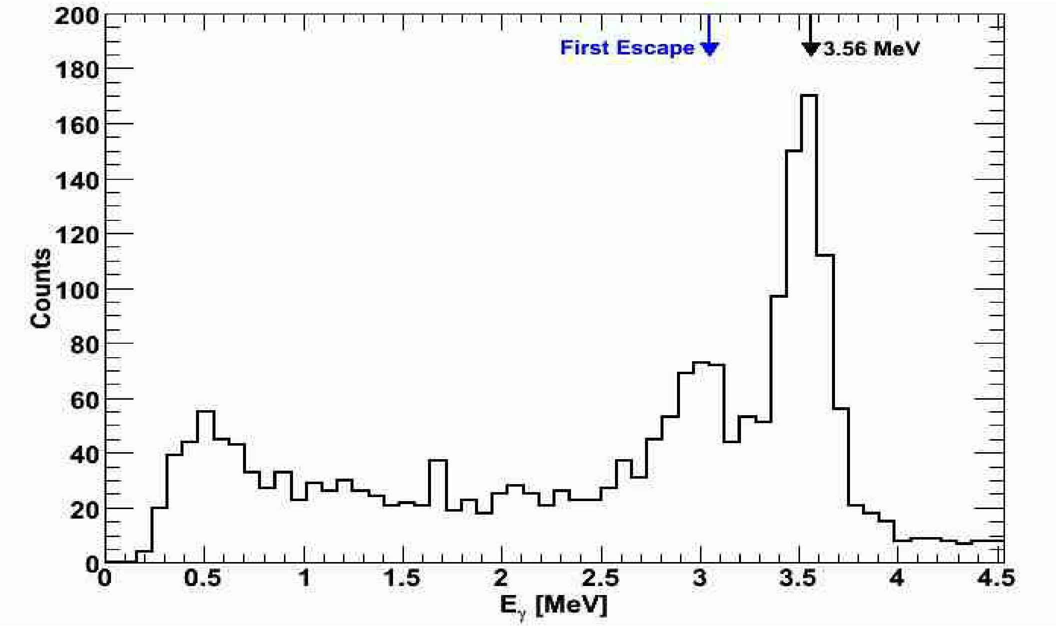
Experiment with CAESAR + HiRA



E*=~~7.05~~ or 10.61 MeV

^{8}B (IAS) formed from a *p*-knockout from ^{9}C beam at MSU.
Detect 2*p*+^{6}Li decay products in HiRA.

Doppler-corrected γ-spectra gated on 2*p*+^{6}Li peak



New class of 2*p* emitter. Single proton emission violates isospin conservation. The only isospin allowed decay is a prompt 2*p* emission. Goldansky-type decay if isospin is conserved

Isobaric Multiplet Mass Equation

If no Coulomb and isospin is a good quantum Number, then mass of neutron = mass of proton.
All members of an isobaric multiplet would have the same mass.

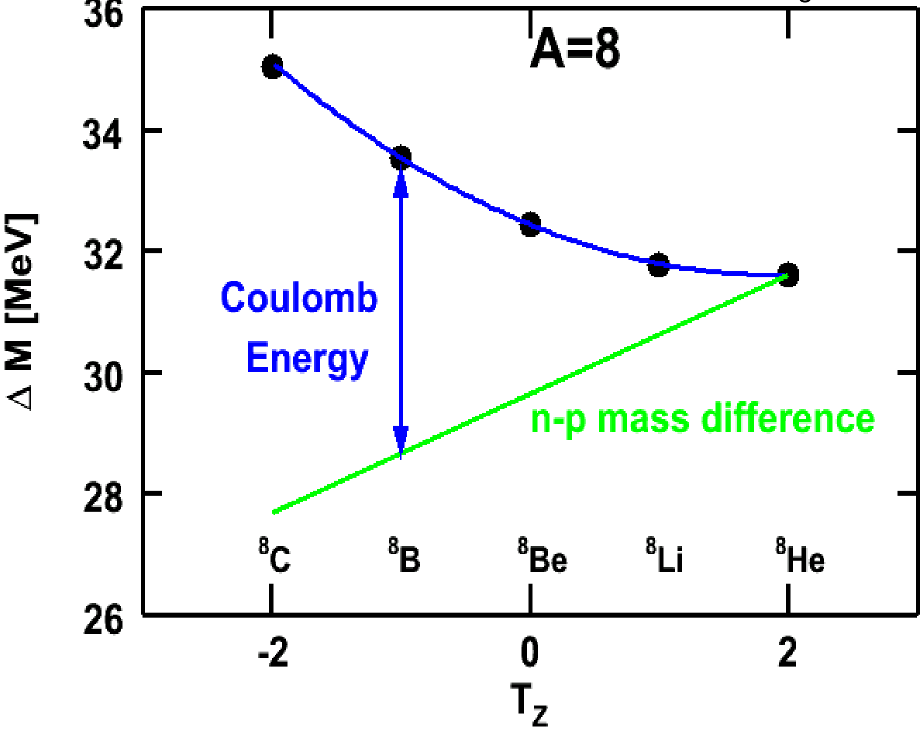
Differences in masses comes mainly from *n-p* mass difference and the Coulomb energy.
Wigner showed that for a multiplet with isospin T, the mass is

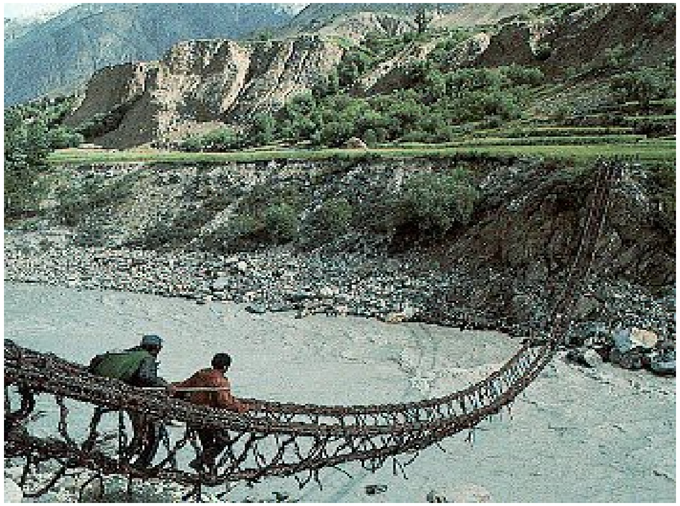
$M(T,T_z) = a + b\,T_z + c\,T_z^2$

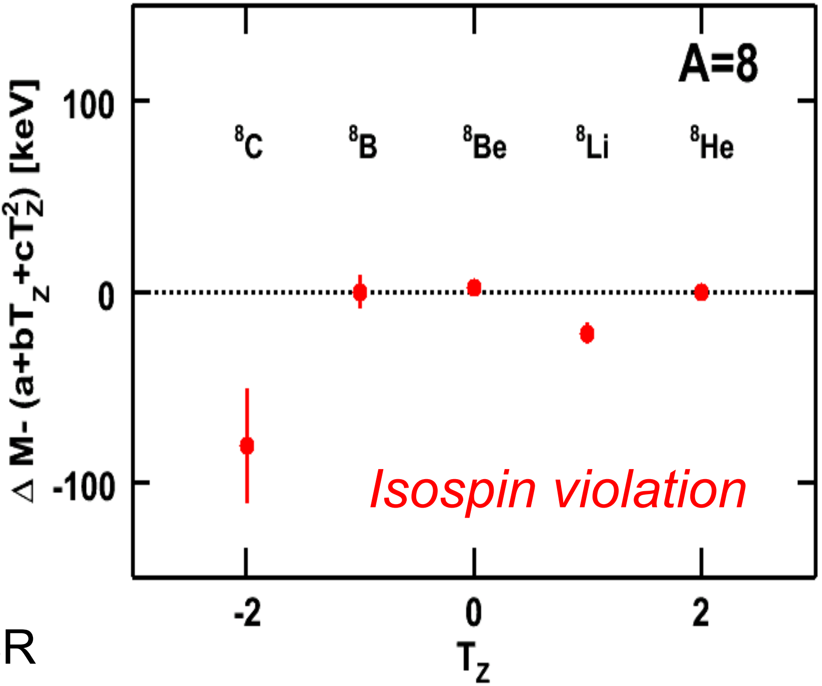
$T_z = (N-Z)/2$ = isospin projection

Deviations to this would be related to non-isospin conserving nuclear forces.
The IMME works quite well, with only a few exceptions.
However, A=8 quintet is the largest deviation known.

New mass measurement of $^8C_{g.s.}$

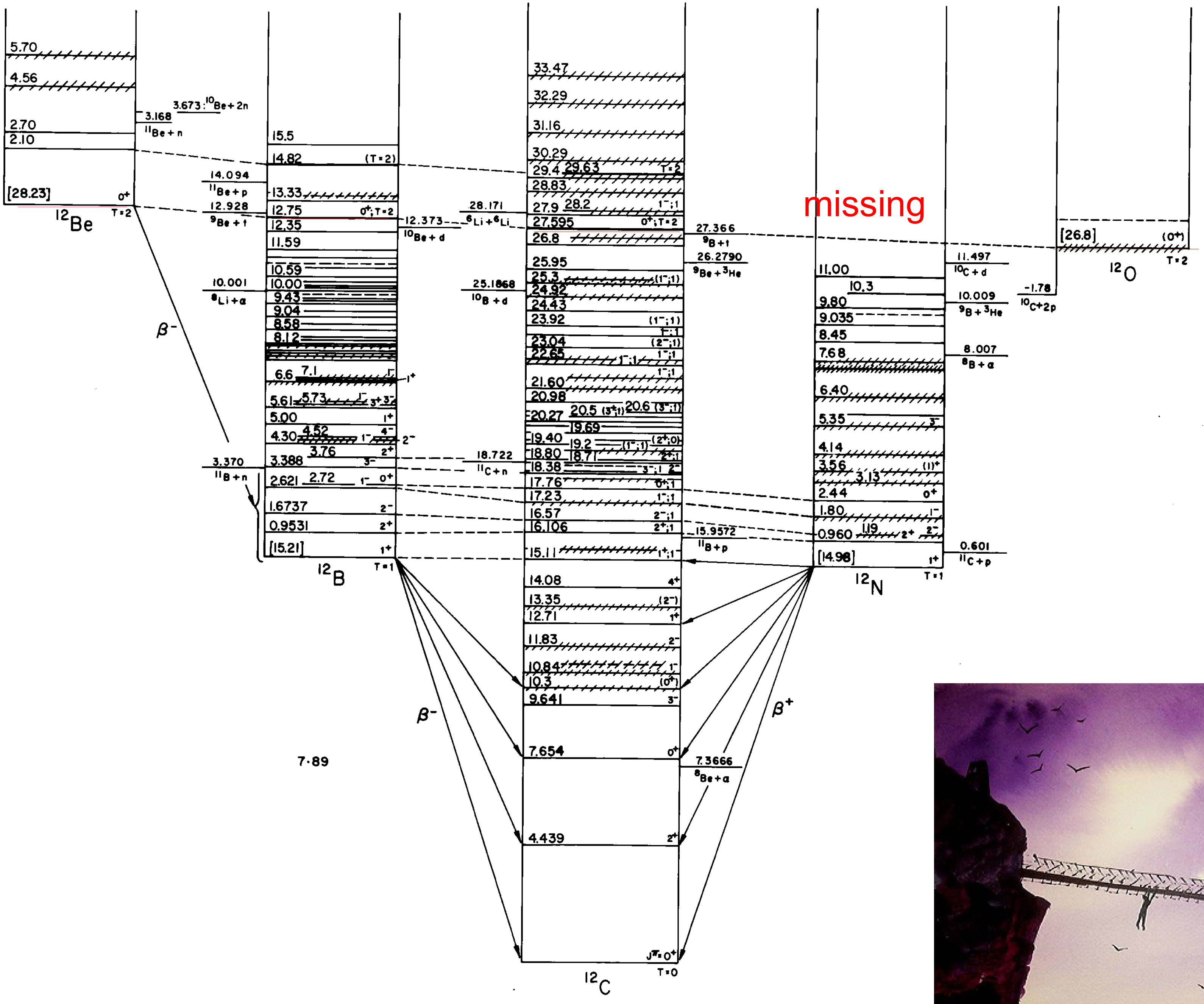






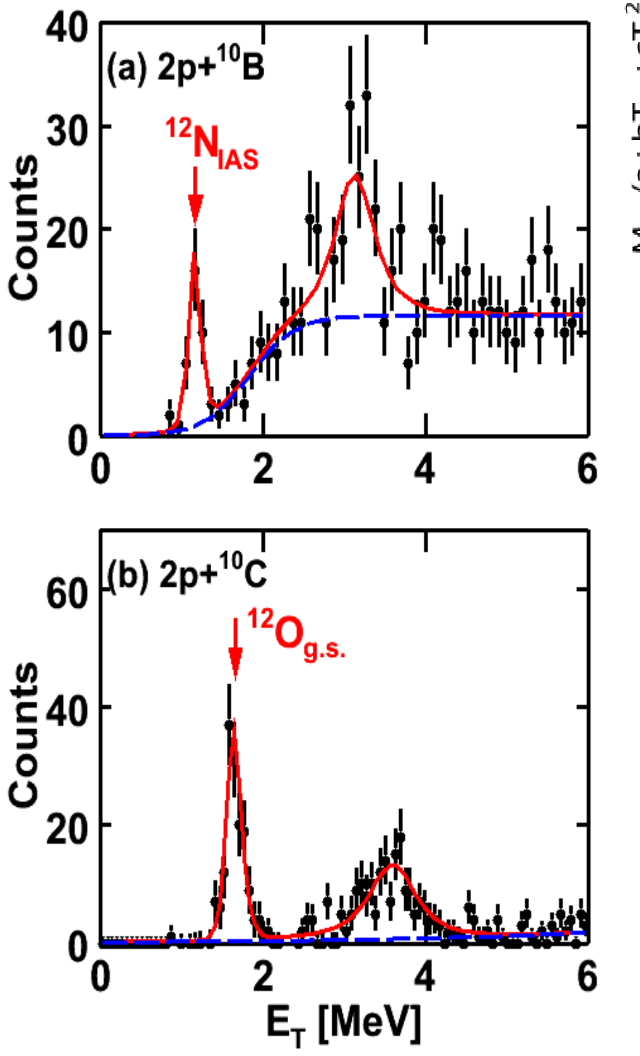
PRC 84 (2011) 051308R

Bridges with missing pieces

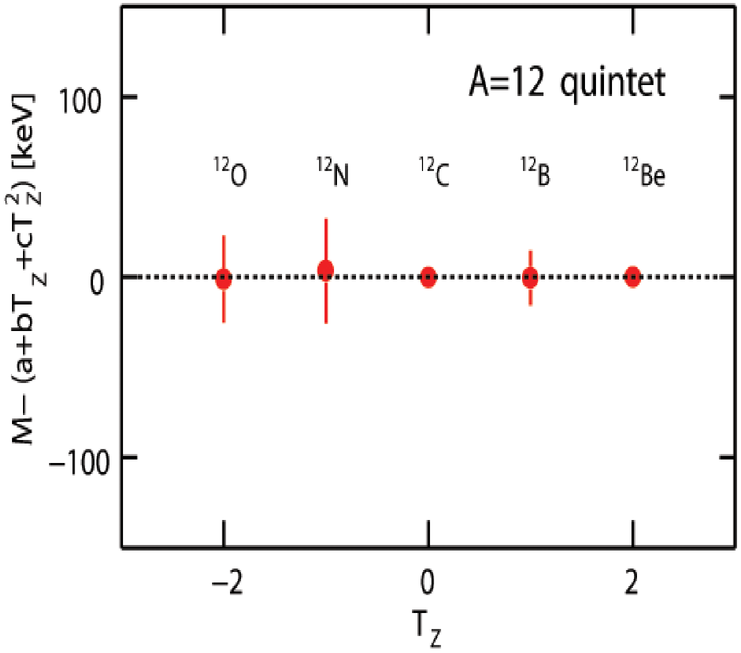


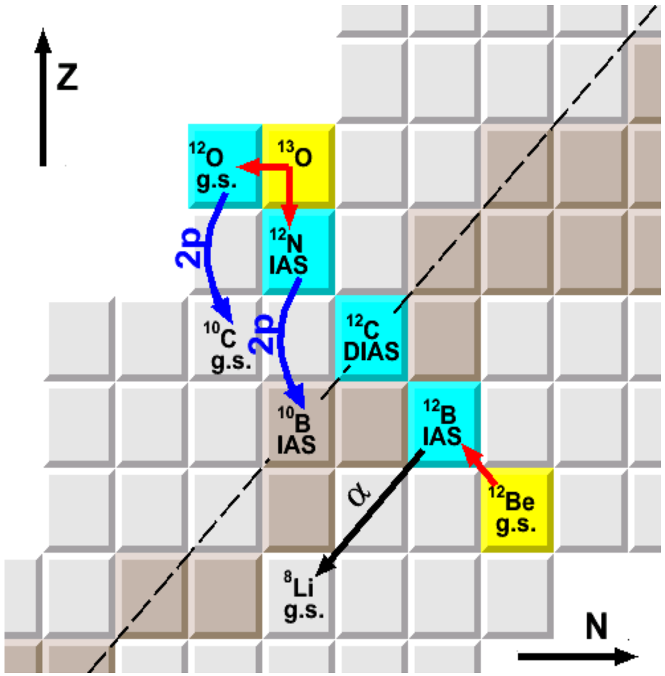
A=12 quintet

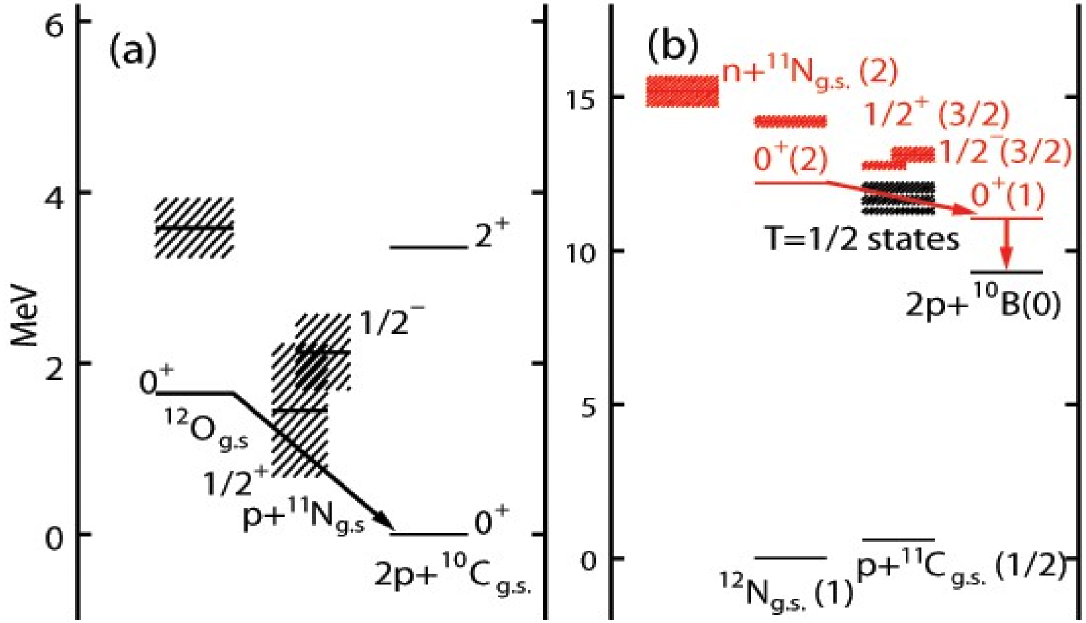
E/A=30 MeV ^{13}O beam
Texas A&M university
^{9}Be target



IMME shows no deviation

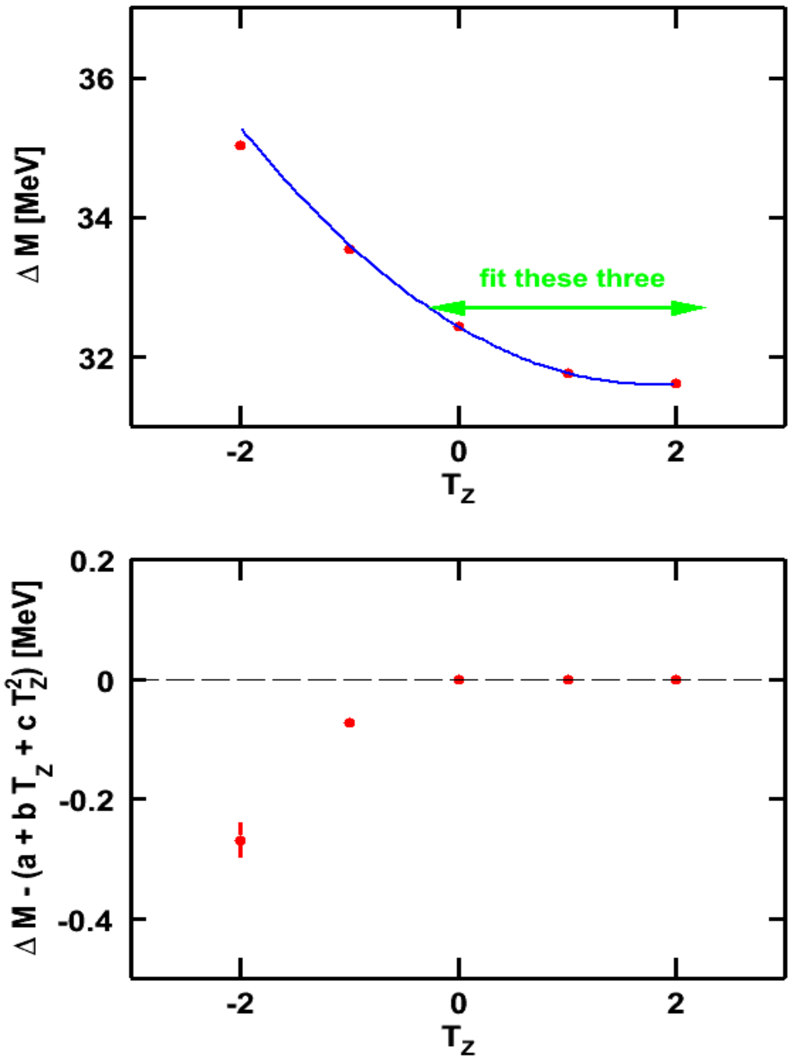




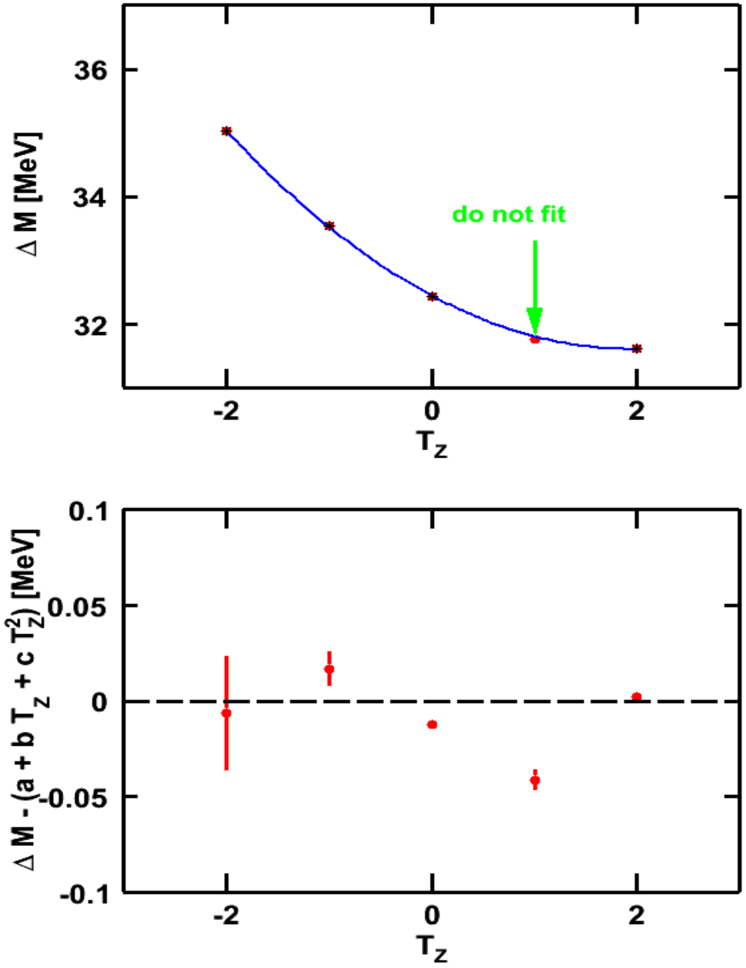


PRC 86 (2012) 011304R

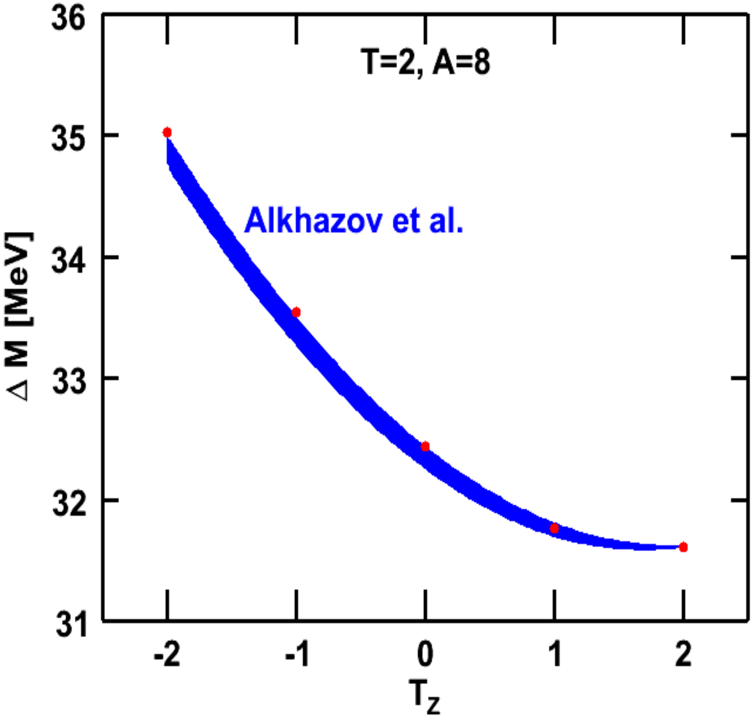
^{12}O$_{gs}$ – new width consistent with theory

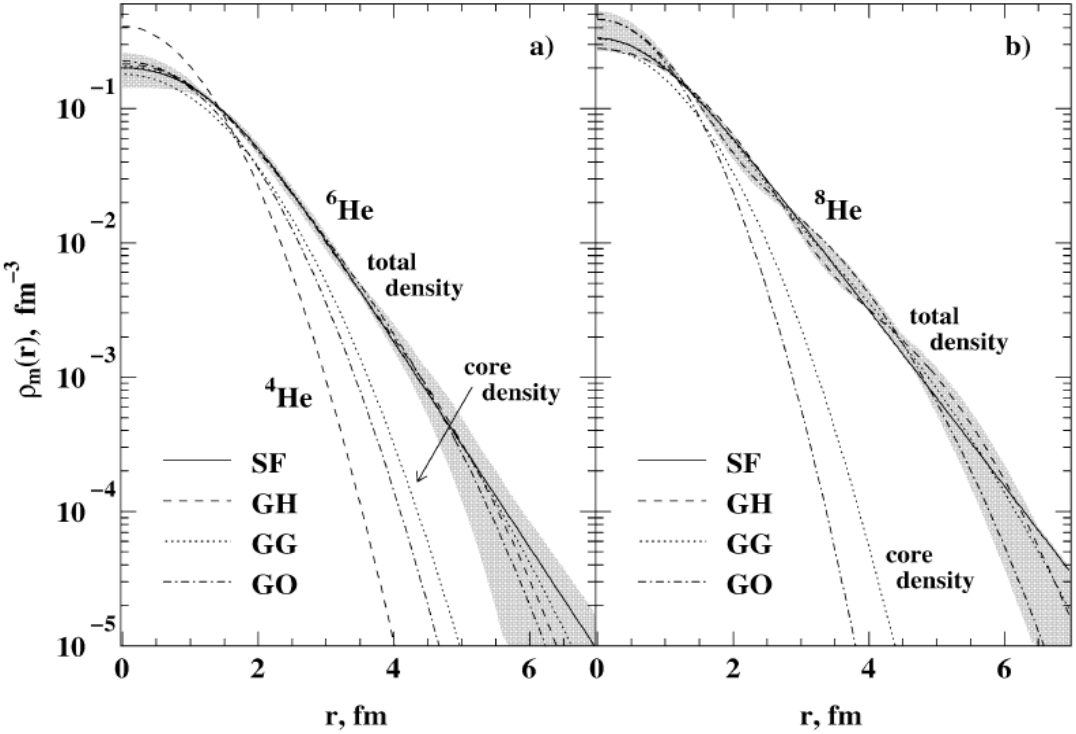


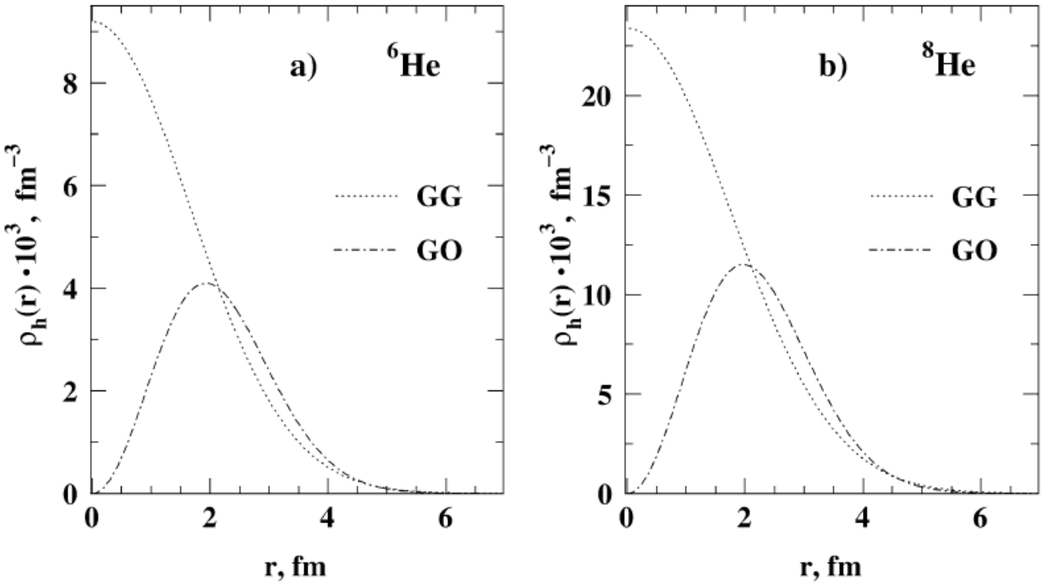
Modification of structure for proton rich Members.



^{8}Li(IAS) energy has only been measured once. Same time as ^{8}Be(DIAS).

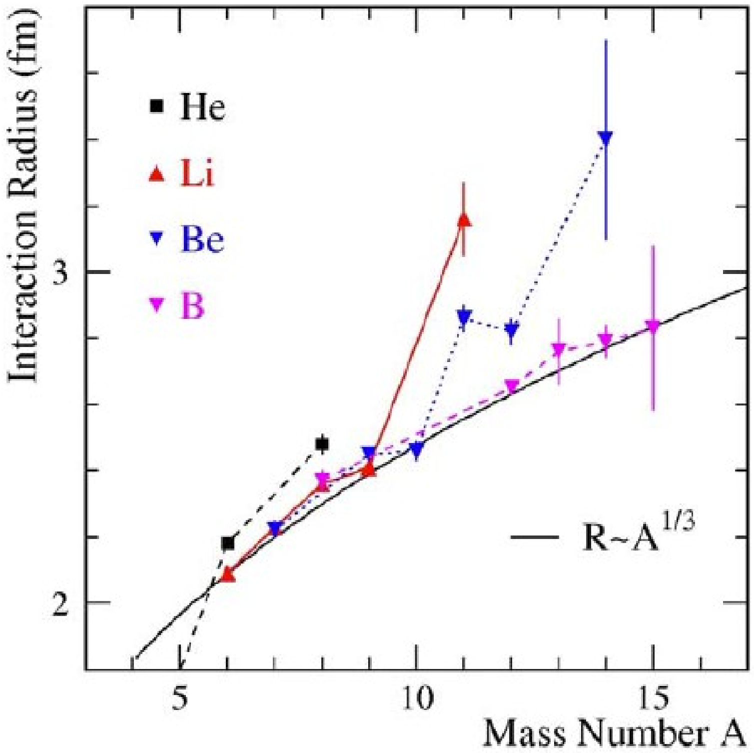




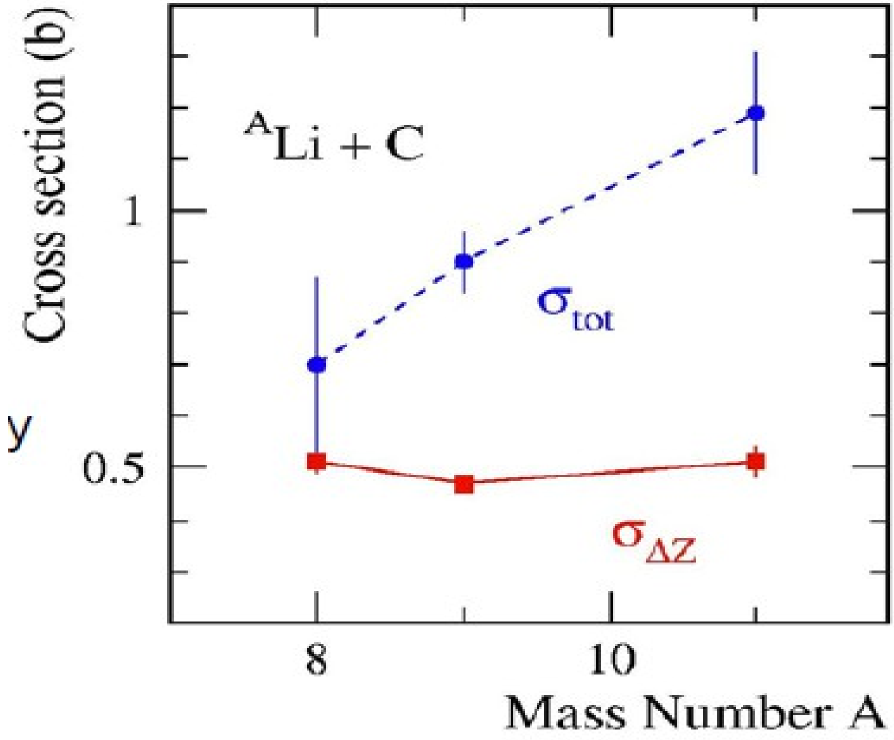


Alkhazov et al
NPA 712 (2002) 269

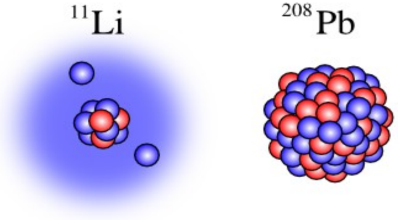
From 0.7 GeV ^{6,8}He + *p* scattering extracted halo distribution. Within level of uncertainity consistent with IMME if halo is frozen.



Tanihata et al,
PRL 55(1985) 2676
PLB 206 (1988) 592



Blank et al.
Z. Phys. A343 (1992) 375



A=11 sextet

Core-Halo model

Suzuki and Yabana
Phys. Lett. B **273**(1991) 173

Core Halo

$$|{}^{11}Li\rangle = |{}^{9}Li_{g.s.}\rangle\ |nn\rangle$$

$$|{}^{11}Be\rangle_{T=5/2} = T_{-}|{}^{11}Li\rangle$$

^{11}Be$_{IAS}$ observed in *n*+*p*+^{9}Li channel
by Teranishi et al PLB 407 (1997) 110.

$$= \left\langle \frac{3}{2},\frac{1}{2},1,1 \middle| \frac{5}{2},\frac{3}{2}\right\rangle |{}^{9}Be\rangle_{T=3/2}\,|nn\rangle$$

$$+ \left\langle \frac{3}{2},\frac{3}{2},1,0 \middle| \frac{5}{2},\frac{3}{2}\right\rangle |{}^{9}Li_{g.s.}\rangle\quad |np\rangle_{T=1}$$

$$= \sqrt{3/5}\ |{}^{9}Be\rangle_{T=3/2}\ |nn\rangle$$

60% n-n halo (stable)

$$+ \sqrt{2/5}\ |{}^{9}Li_{g.s.}\rangle\quad |np\rangle_{T=1}$$

40% n-p halo

$$|{}^{11}B\rangle_{T=5/2} = T_{-}|{}^{11}Be\rangle_{T=5/2}$$

$$= \sqrt{3/10}\ |{}^{9}B\rangle_{T=3/2}\ |nn\rangle$$

30% n-n halo (stable)

$$+ \sqrt{6/10}\ |{}^{9}Be\rangle_{T=3/2}|np\rangle_{T=1}$$

60% n-p halo

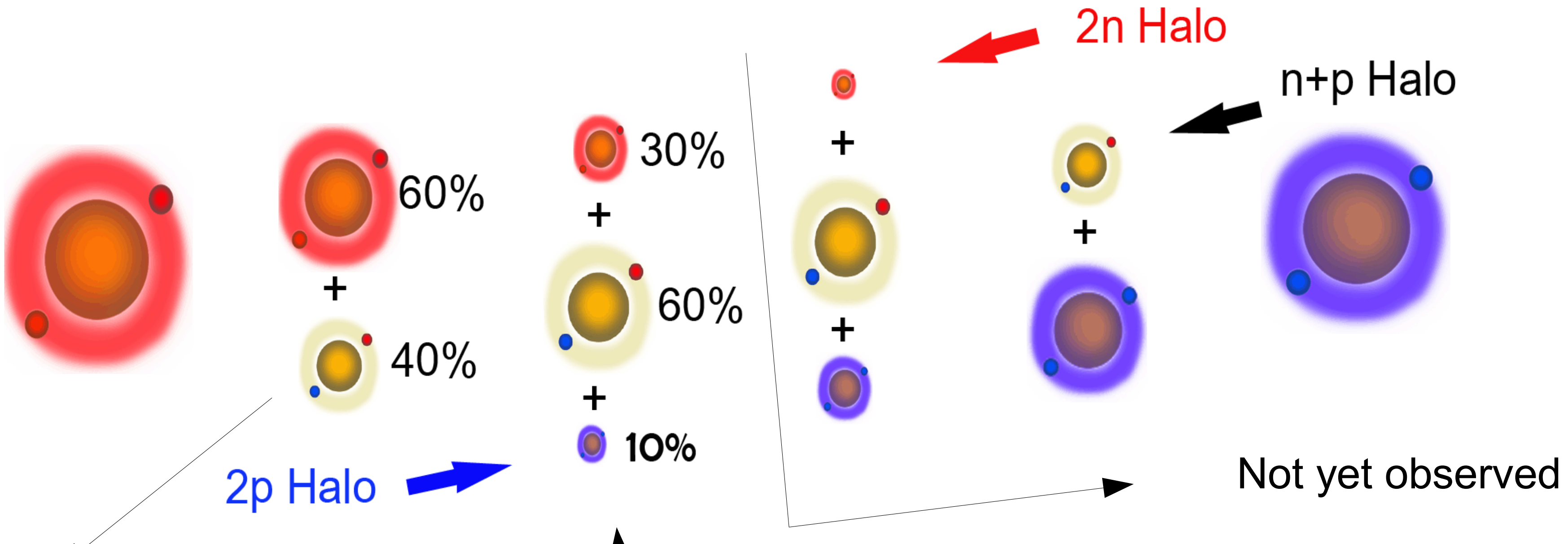
$$+ \sqrt{1/10}\ |{}^{9}Li_{g.s.}\rangle\quad |pp\rangle$$

10% p-p halo

T=5/2 Sextet in A=11

Core-halo model of Suzuki +Yabana PLB 272 (173) 1991

T_z=	5/2	3/2	1/2	-1/2	-3/2	-5/2
	$^{11}\mathrm{Li}_{gs}$	$^{11}\mathrm{Be}_{IAS}$	$^{11}\mathrm{B}_{DIAS}$	$^{11}\mathrm{C}_{DIAS}$	$^{11}\mathrm{N}_{IAS}$	$^{11}\mathrm{O}_{gs}$



2n Halo

n+p Halo

2p Halo

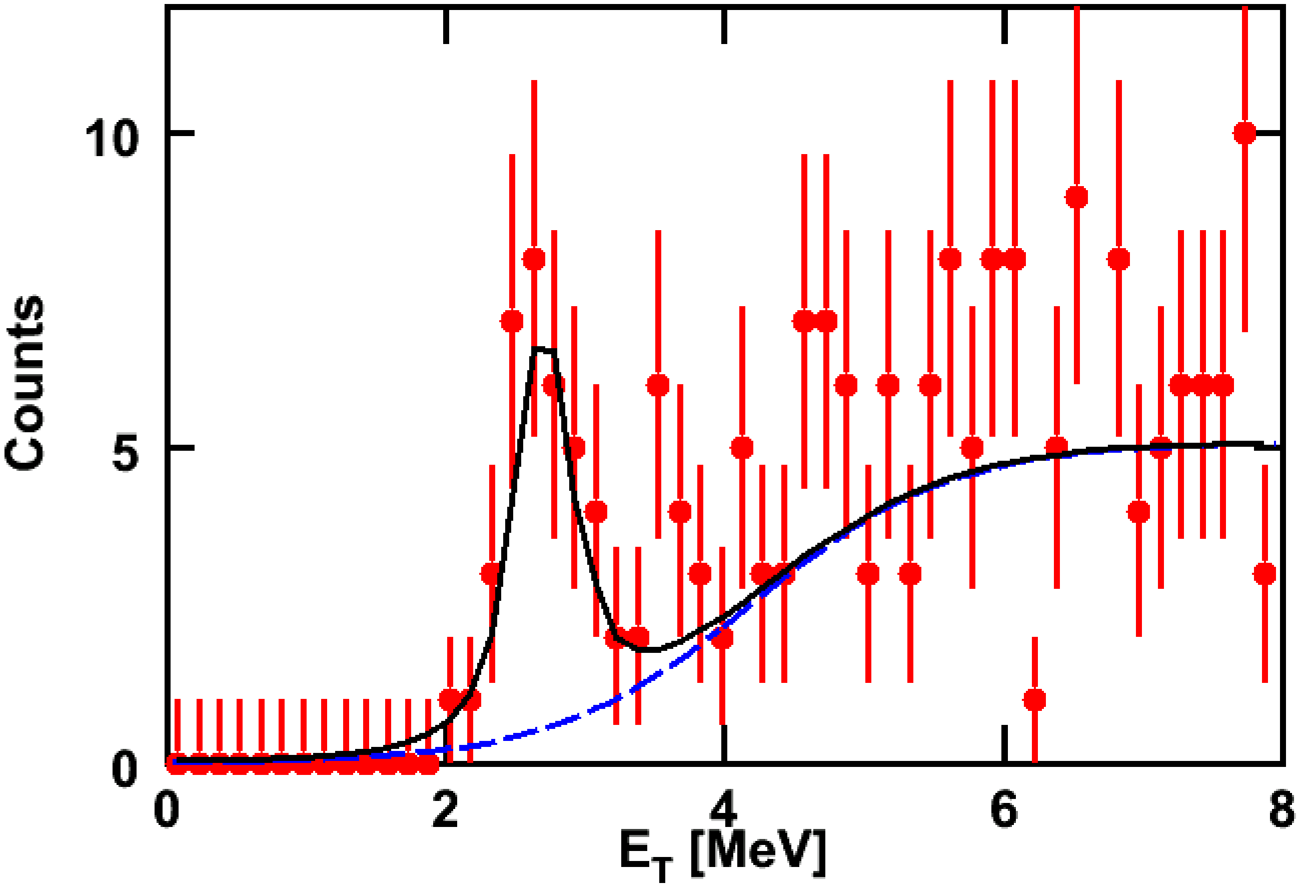
Not yet observed

Observed at RIKEN in 1997
in *p*+*n*+^{9}Li channel

E*=21.2 MeV, Γ=490(70) keV
PLB 407 (1997) 110

Double Isobaric analog of ^{11}Li in ^{11}B

^{12}Be beam @E/A= 50 MeV with carbon and polyethylene targets.
See peak with Polyethylene target but not with ^{12}C target
Reaction ^{12}Be(p,2n)^{11}B
For 2p decay branch σ=72(21)μb, should also have a n+p decay branch



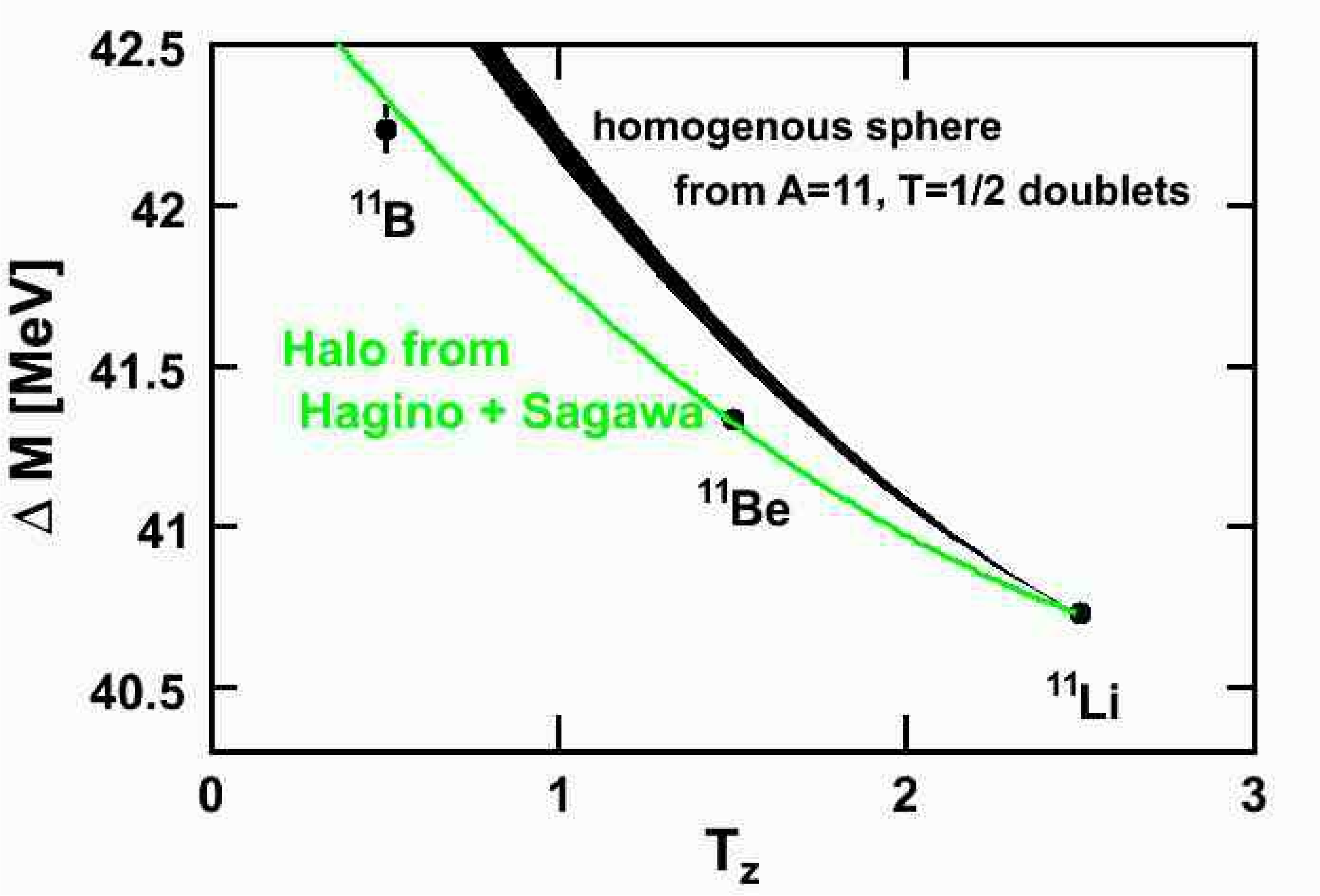
$^{11}\mathrm{B} \rightarrow 2p + {}^{9}\mathrm{Li}$

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

Fit include detector resolution

Decay kinetic energy

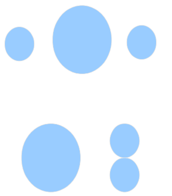
Isobaric Multiplet Mass Equation for A=11, T=5/2



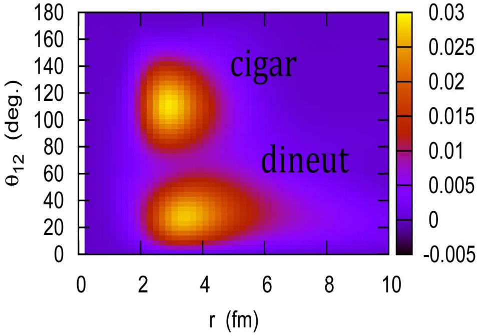
Reduced Coulomb energy compared to expectation from A=11, T=1/2 doublets. Confirmation of Halo structure. Consistent with ^{11}Li Halo wavefunctions calculated by Hagino and Sagawa [P(s^2)=0.23] and assuming Halo wavefunctions are frozen along sextet.

PRC 86 (2012) 041307

How much $(s_{1/2})^2$ configuration is these in ^{11}Li in addition to the $(p_{1/2})^2$

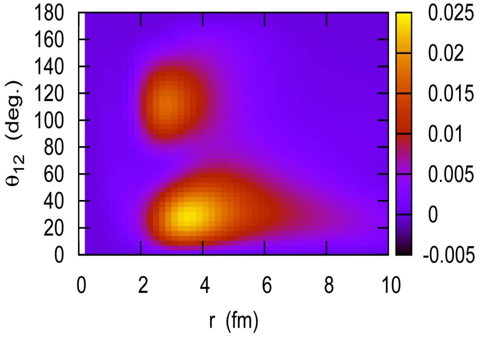


$P(s^2)$=23%



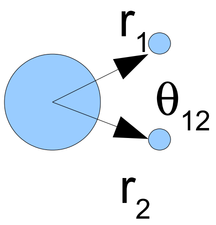
Consistent with
Measured dipole
response

$P(s^2)$=50%



Consistent with
measured charge
radius

$r=r_1=r_2$



From Hagino

The dineutron configuration gives us the halo. The IMME is dependent on the radial extent of the halo (dineutron component fraction) which is dependent on $P(s^2)$.

The physics is similar to the Thomas-Ehrman shift.

Correlations in 3-body decay

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

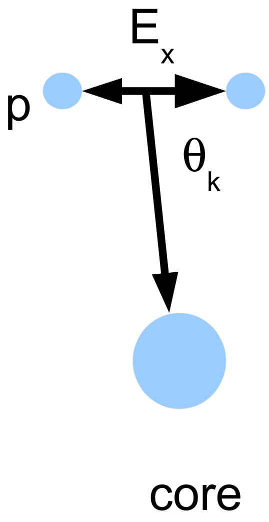
Remove:

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 information.

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

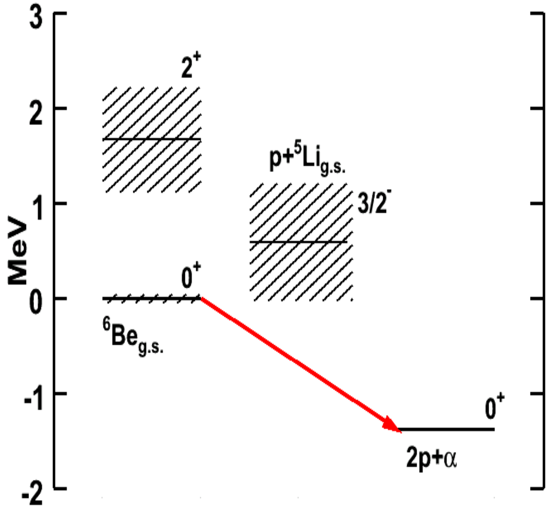
Jacobi T hyperspherical coordinates



E_x- relative KE between 2 protons

E_T -total decay KE.

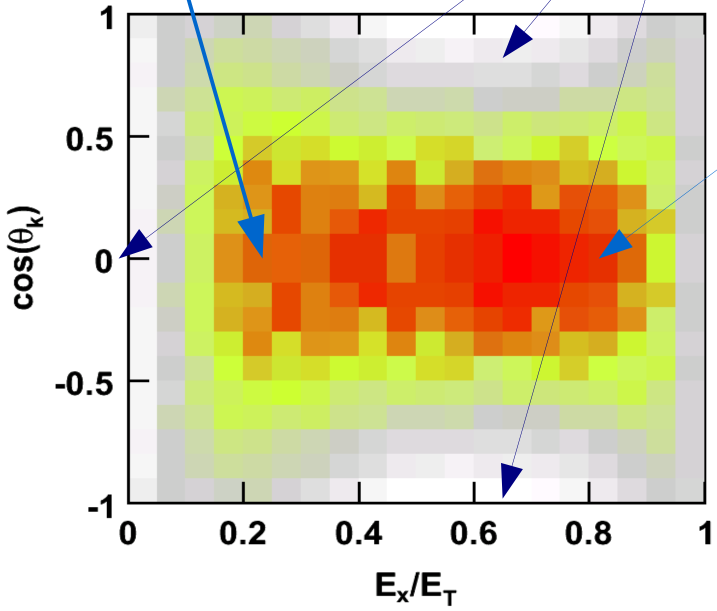
Prompt Decay



Coulomb Suppressions

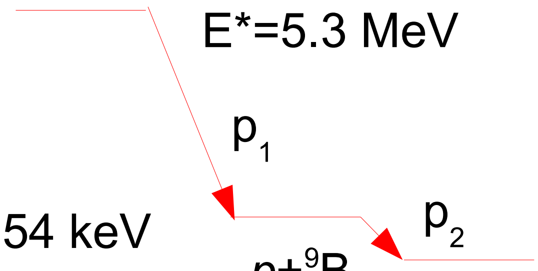
“diproton”

“cigar”



Sequential decay

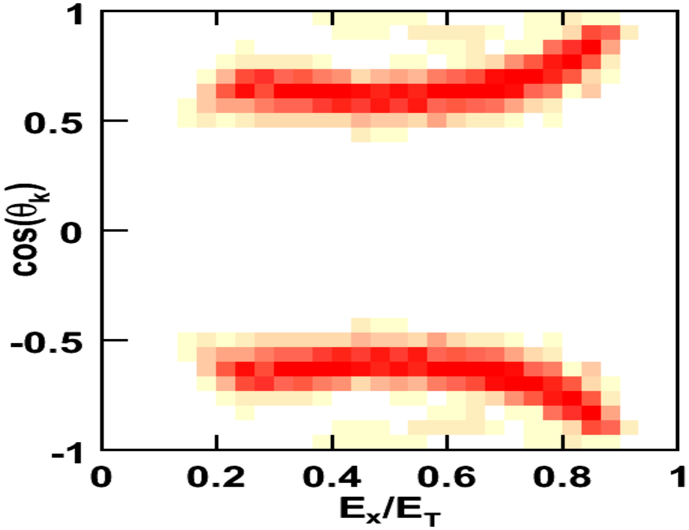
^{10}C
E*=5.3 MeV



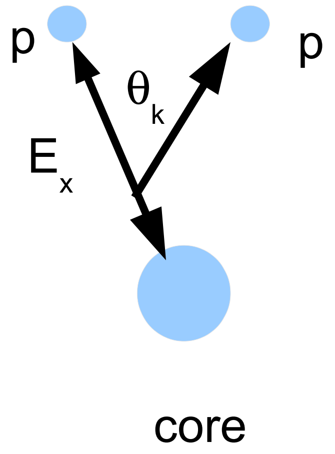
Γ=0.54 keV

p+^{9}B$_{g.s}$.

2p+^{8}Be$_{g.s.}$



Jacobi Y hyperspherical coordinates

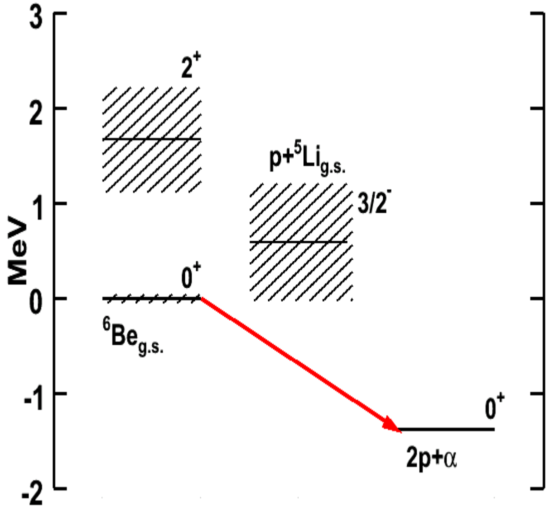


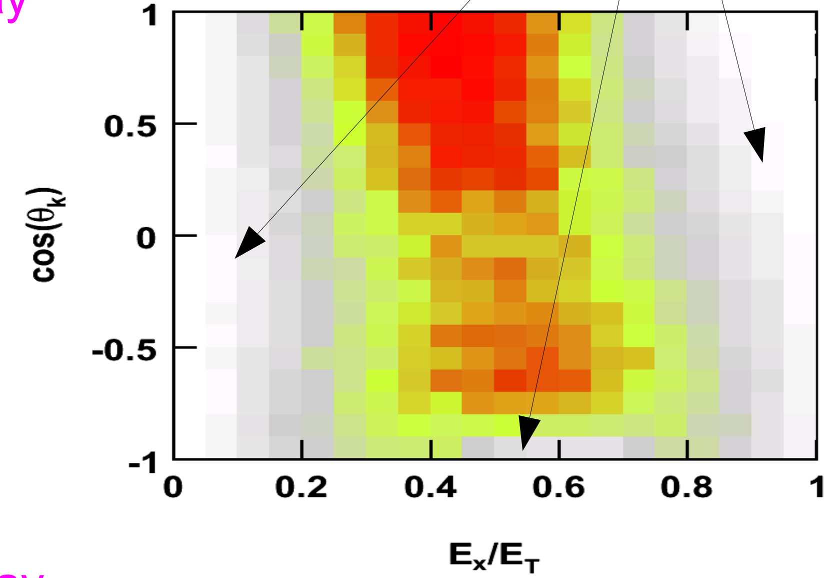
E_x - relative KE between proton and core

E_T -total decay KE.

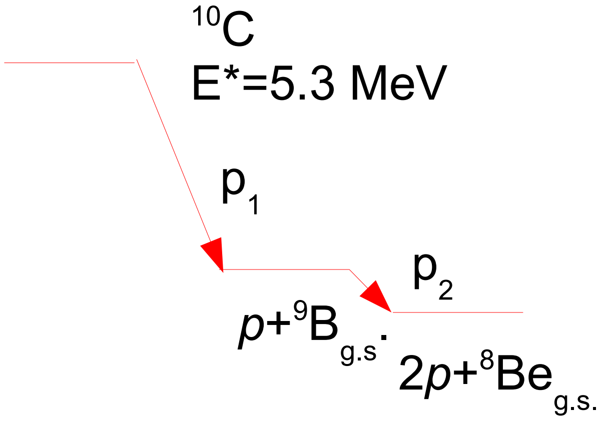
Coulomb Suppressions

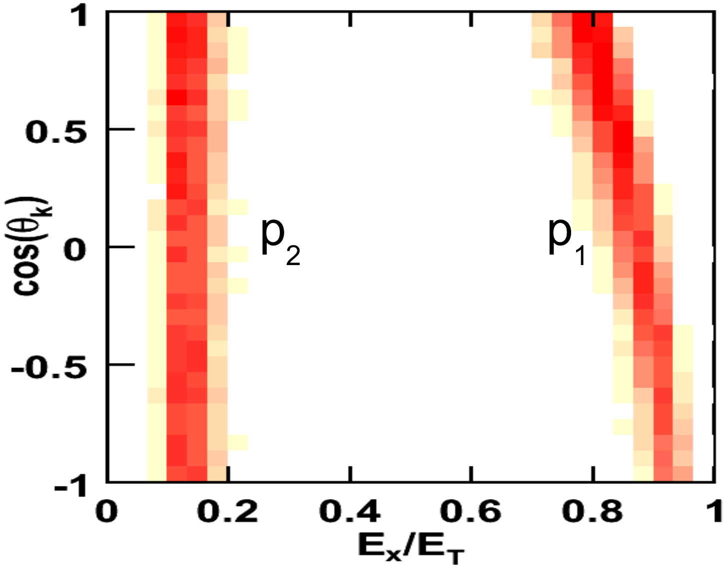
Prompt Decay

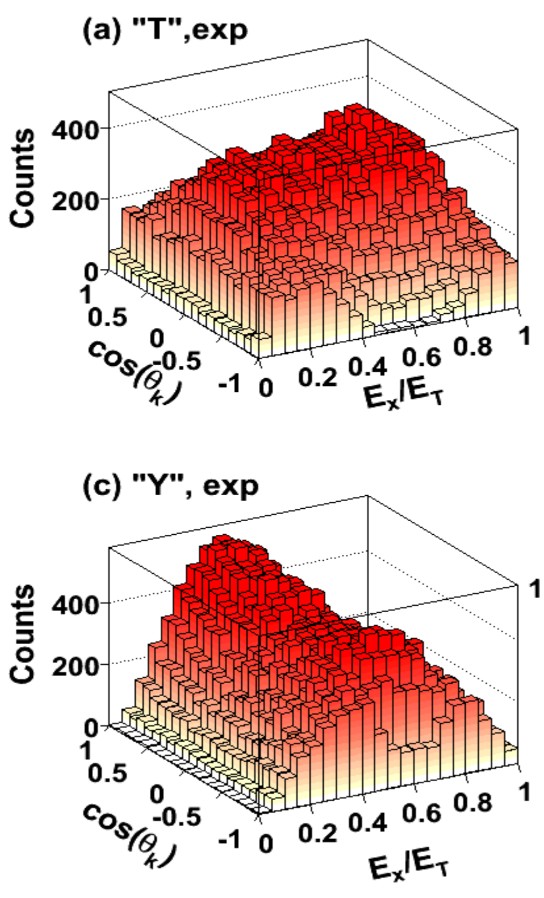




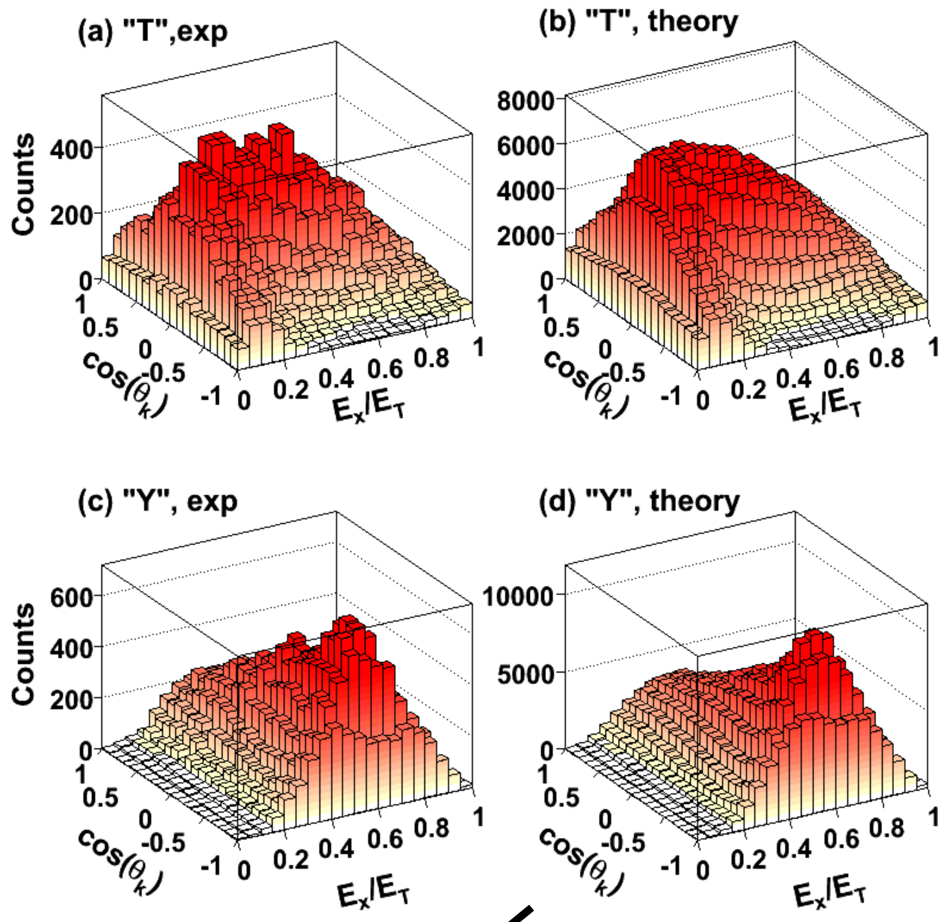
Sequential decay





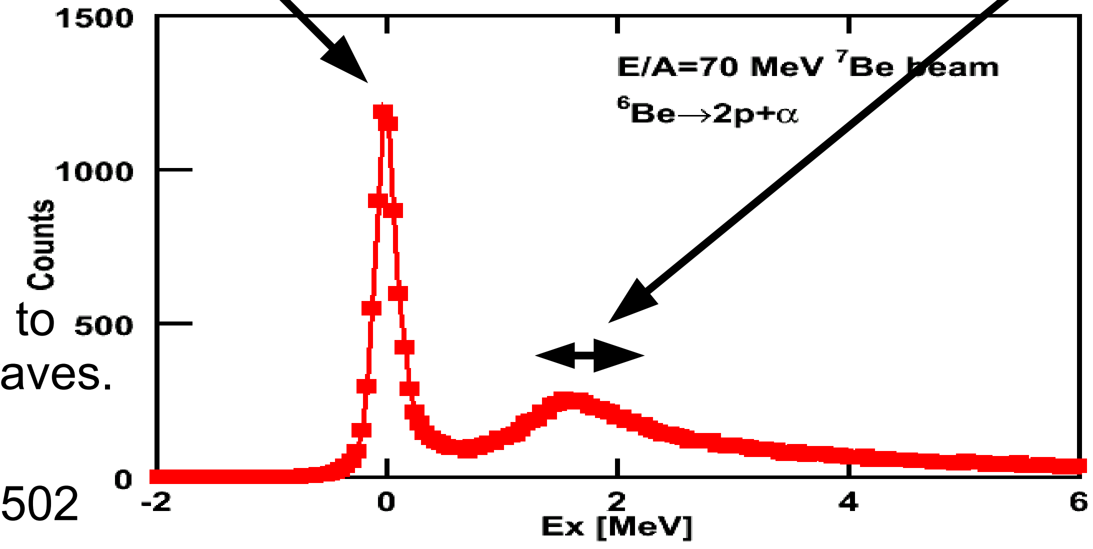


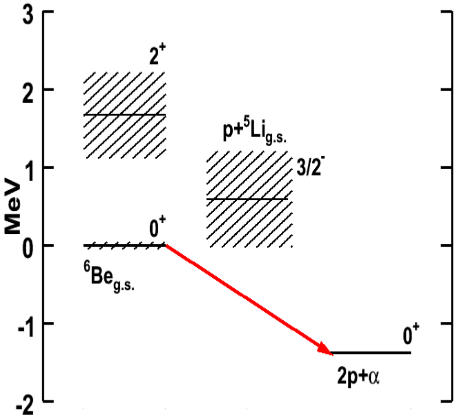
^{6}Be ground-state 0^+



^{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

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

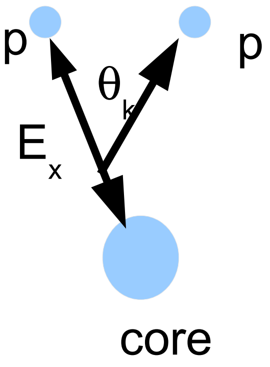
a)Less dependent of calculation details

b)Less dependent on detector bias

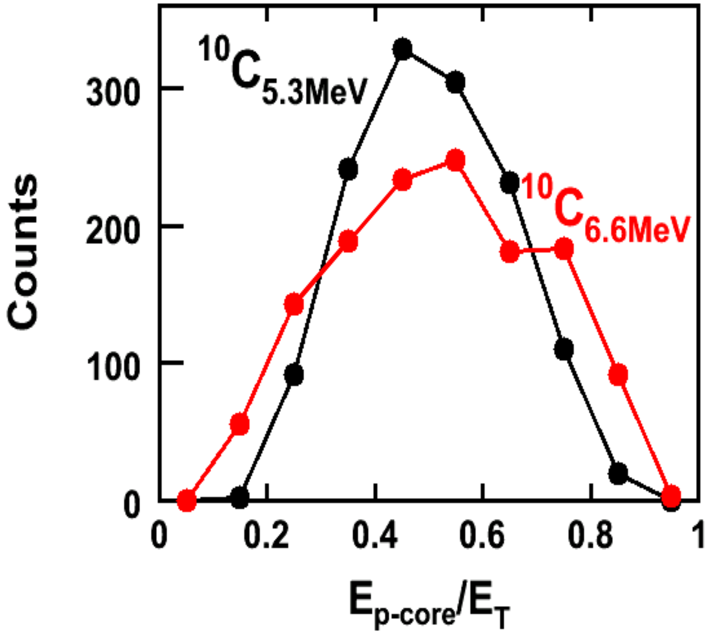
c) Goldansky ~$P(E_x)P(E_T-E_x)$

Product of 2 penetration factors

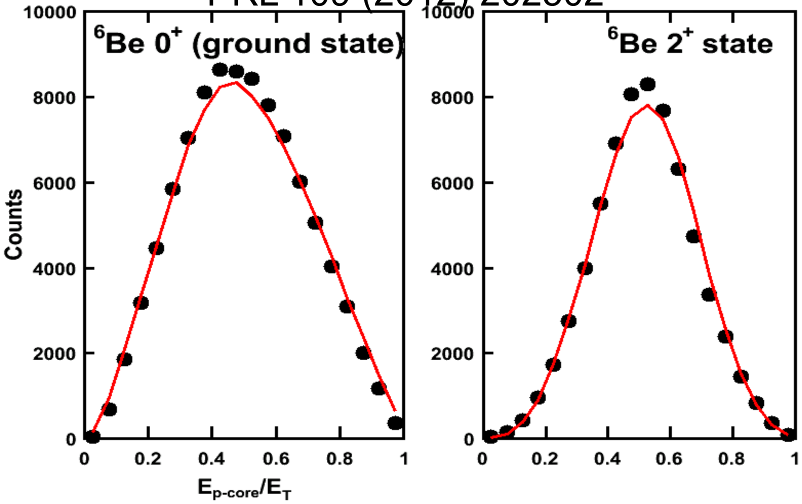
Peaks at $E_x=E_T/2$

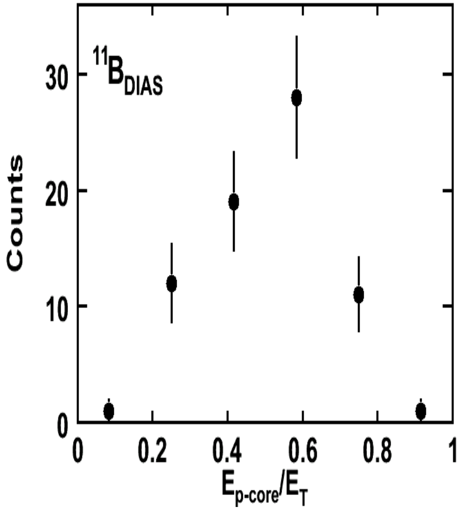


PRC 80 (2009) 024306

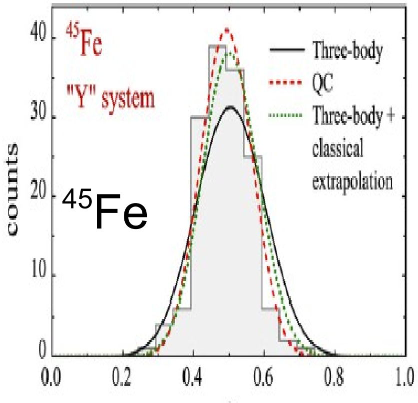


PRL 109 (2012) 202502

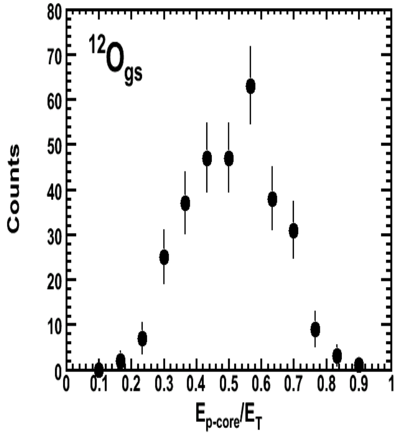




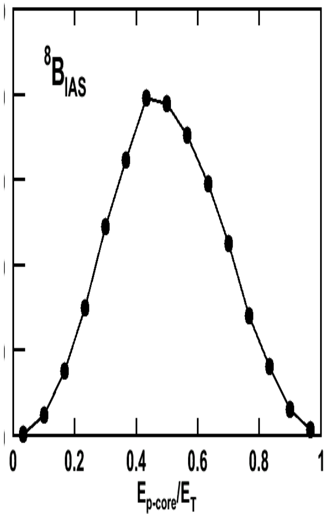
PRC 86 (2012) 041307.

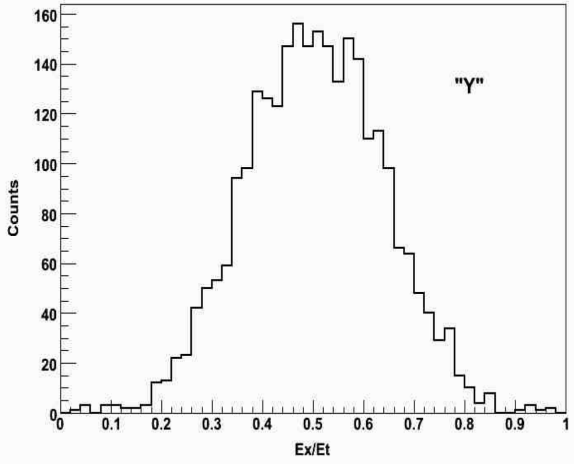


PRL99(2007)192501



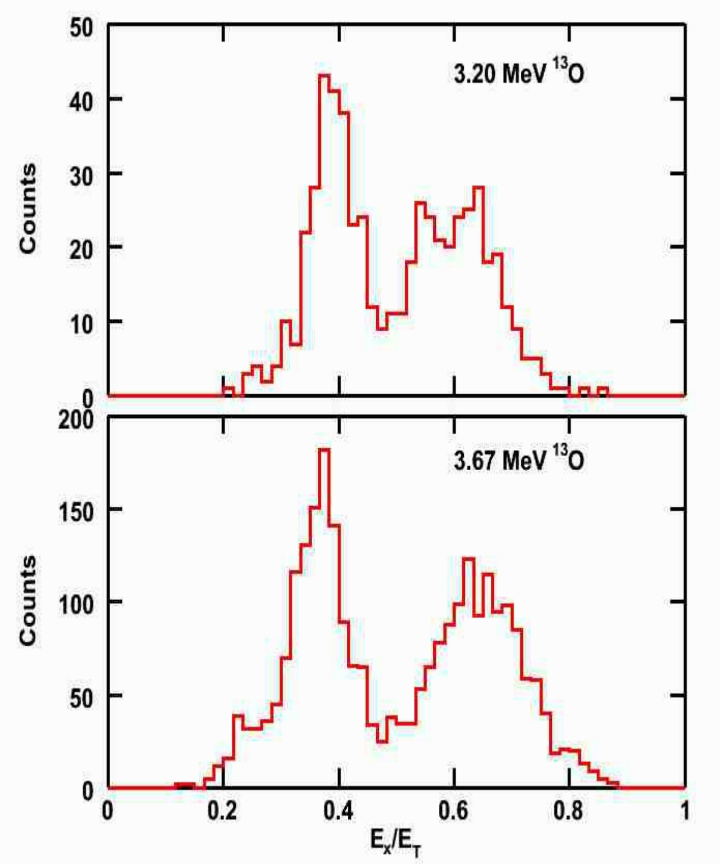
PRC 86 (2012) 011304R

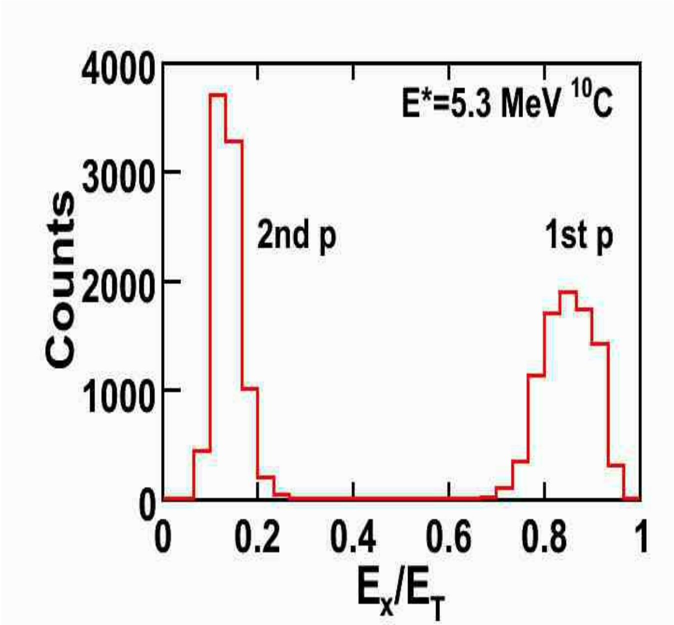


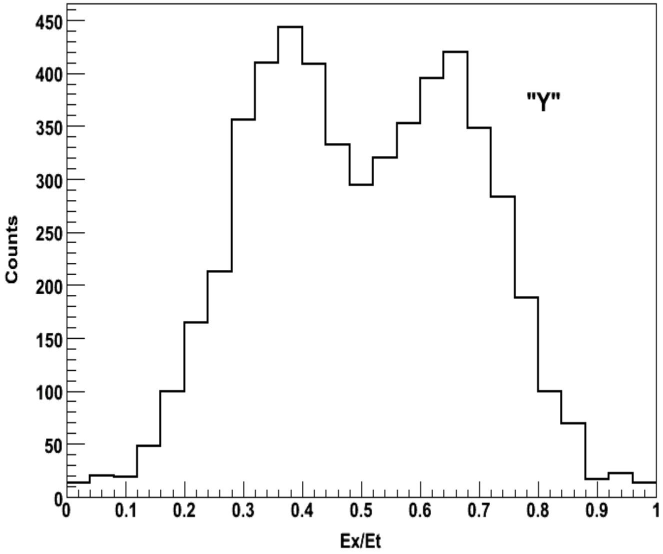


^{16}Ne ground state

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

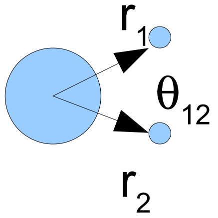


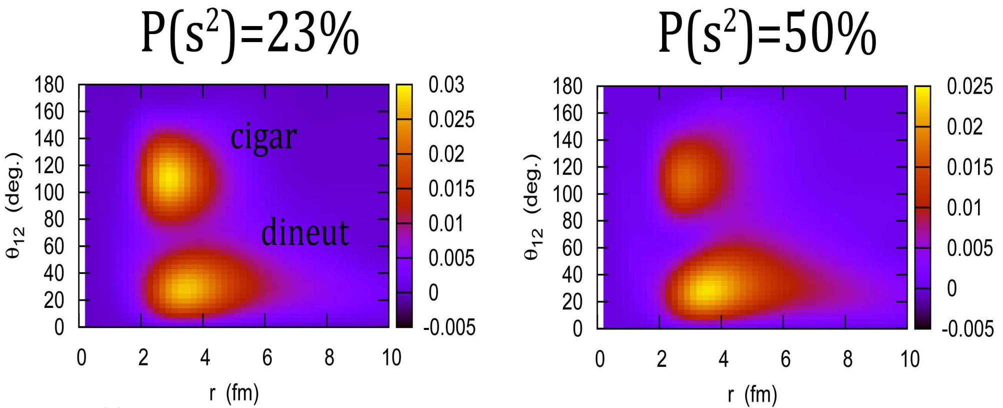




^{16}Ne first excited state

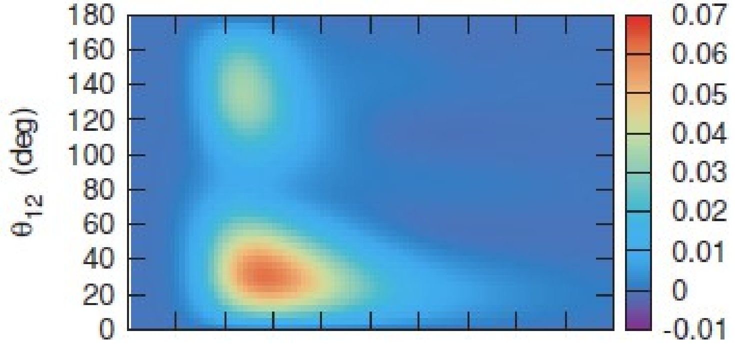
Can we see the correlations in the halo of the 2*p* emitters





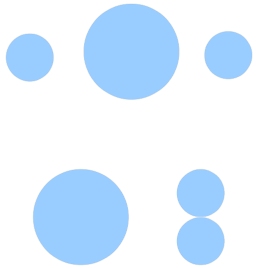
^{11}Li

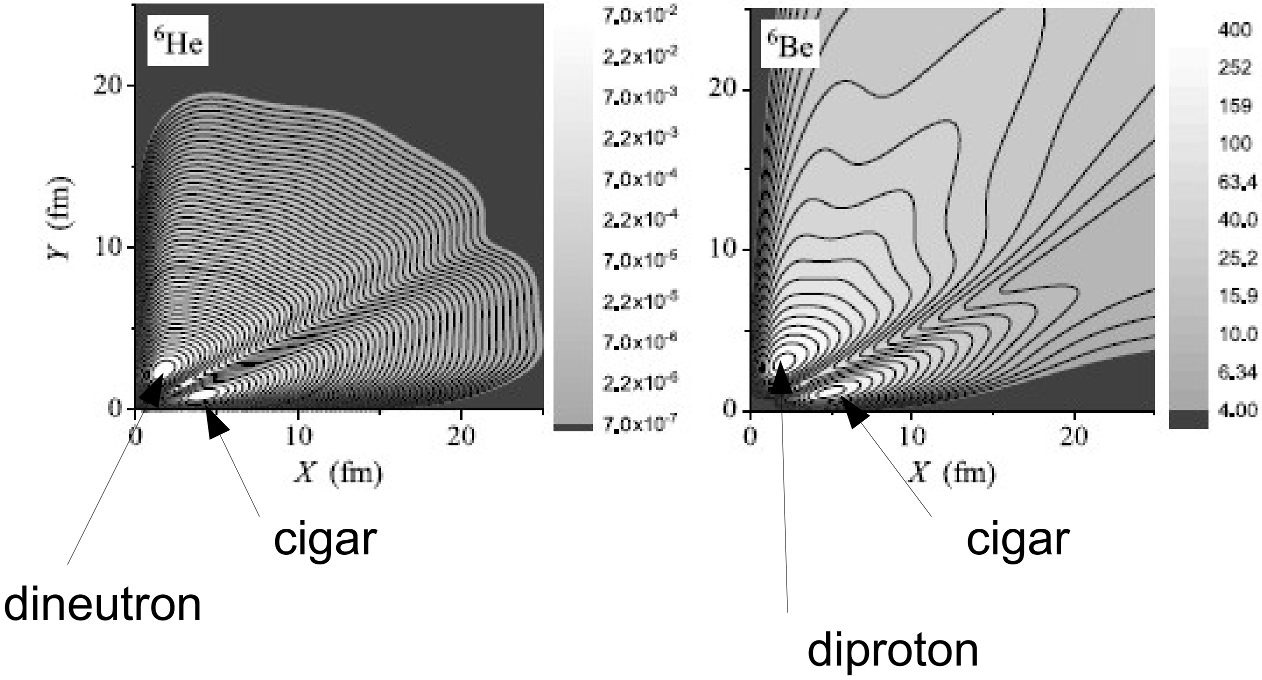
$r = r_1 = r_2$



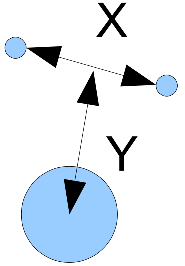
(Hagino + Sagawa PRC 72(2005)044321)

^{6}He

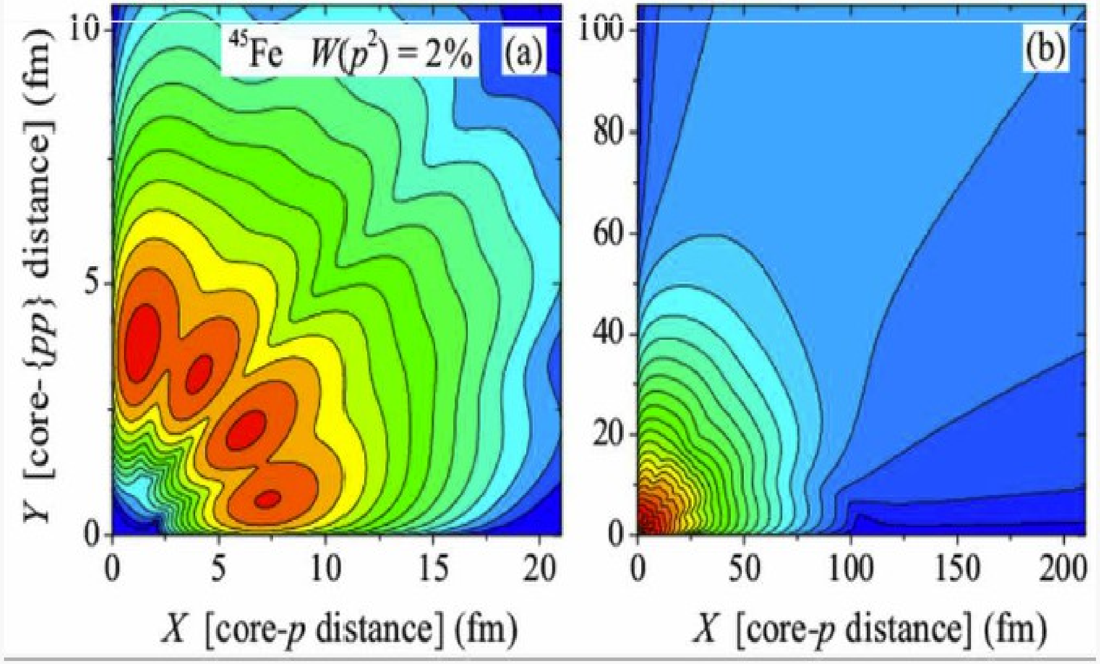




Grigorenko PRC 80 (2009) 034602

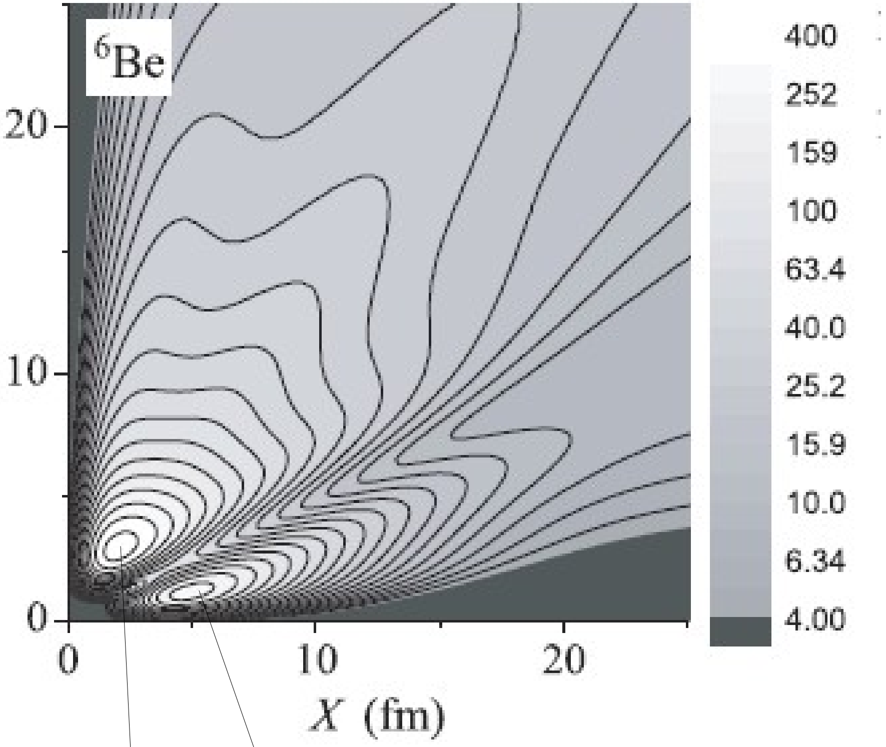


The ^{45}Fe wave function density in the T system for the configuration $98\% f^2 + 2\% p^2$



Grigorenko and Zhukov, PRC 68 (03) 054005

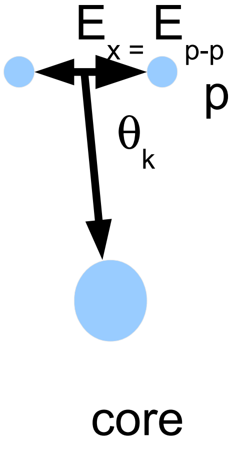
M.P. et al, RMP (2012) 567



ground state of ^{6}Be has similar amounts of diproton and cigar configurations.

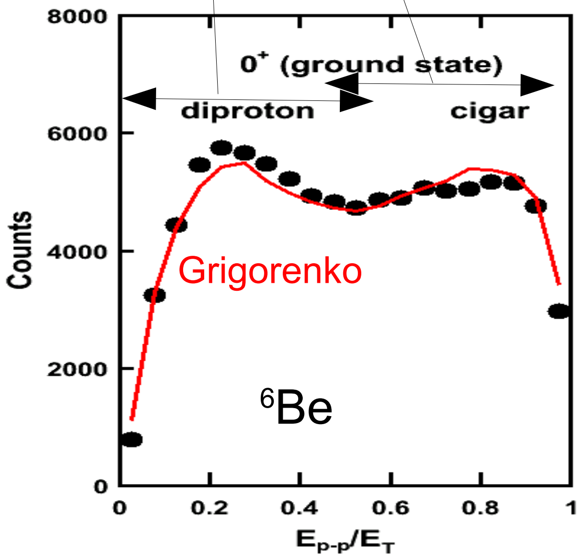
2^+ state has more diproton

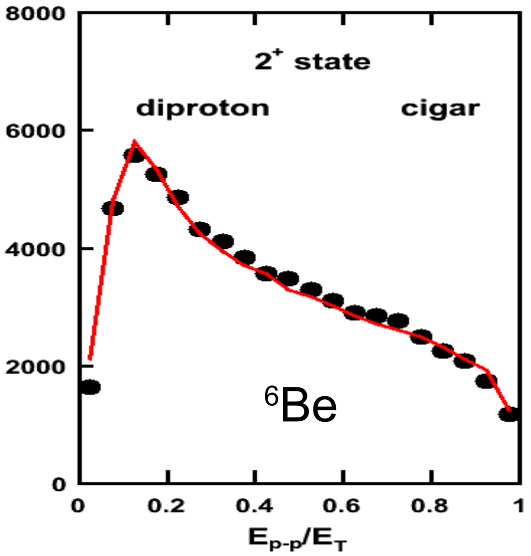
^{11}B(DIAS) is ~ similar to ^{6}Be$_{g.s.}$

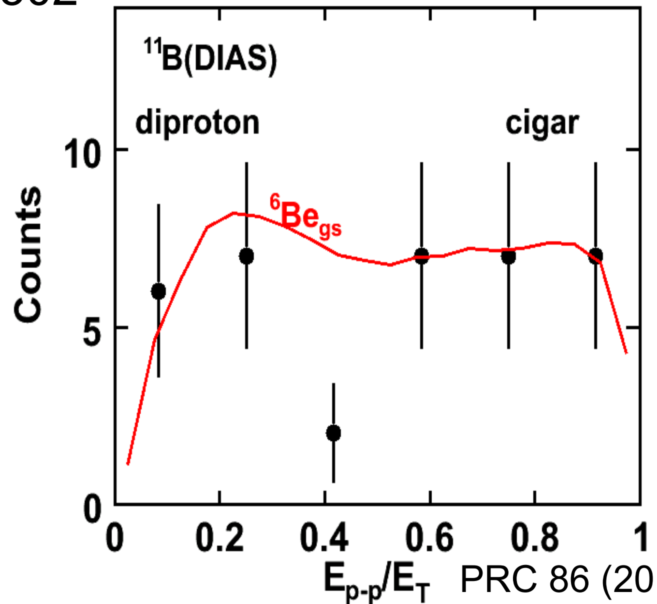


Jacobi T

PRL 109 (2012) 202502



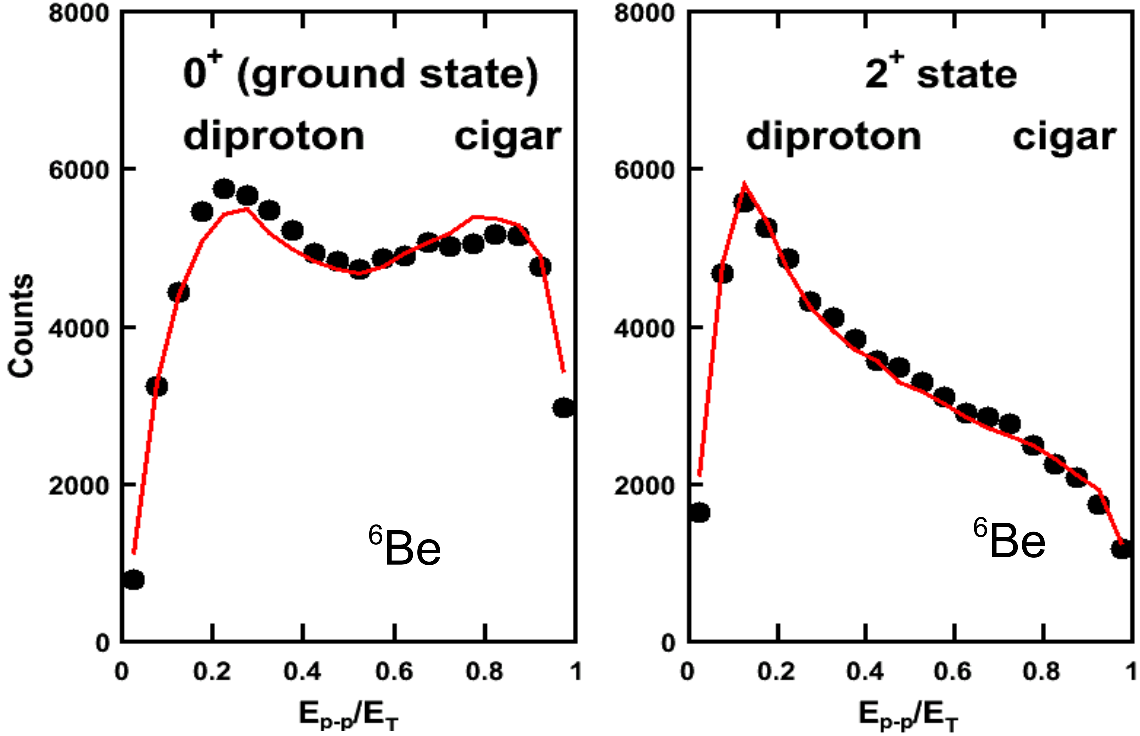


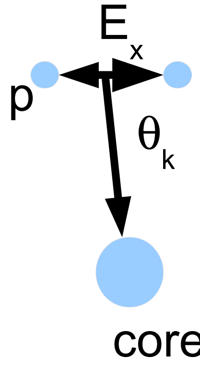


PRC 86 (2012) 041307.

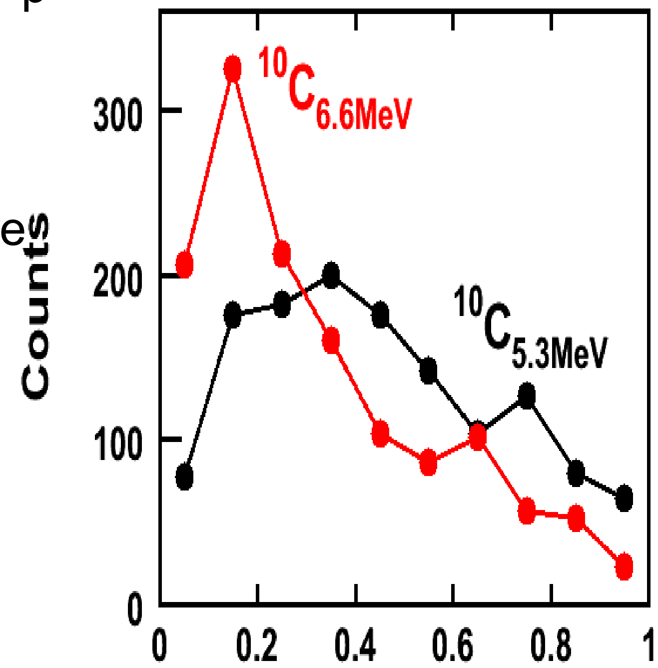
Systematic of $E_{p\text{-}p} = E_x$ Jacobi T

PRL 109 (2012) 202502

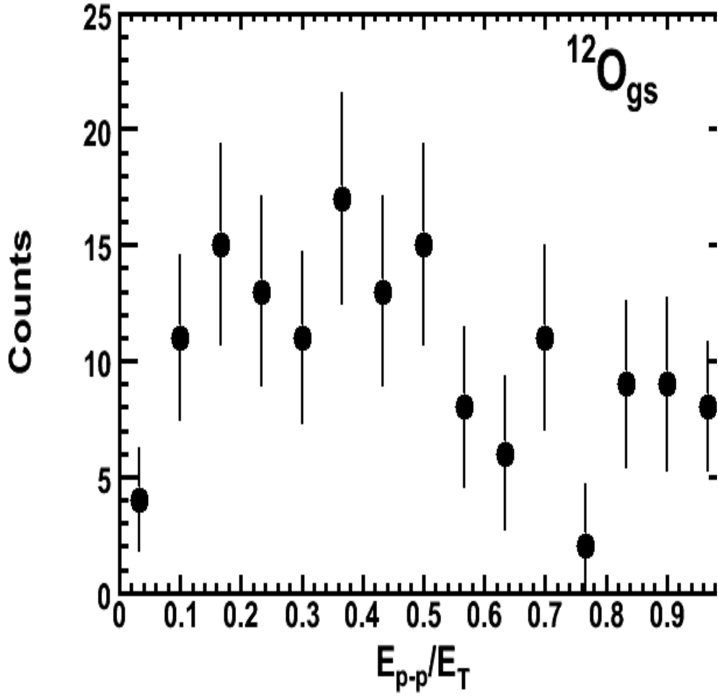


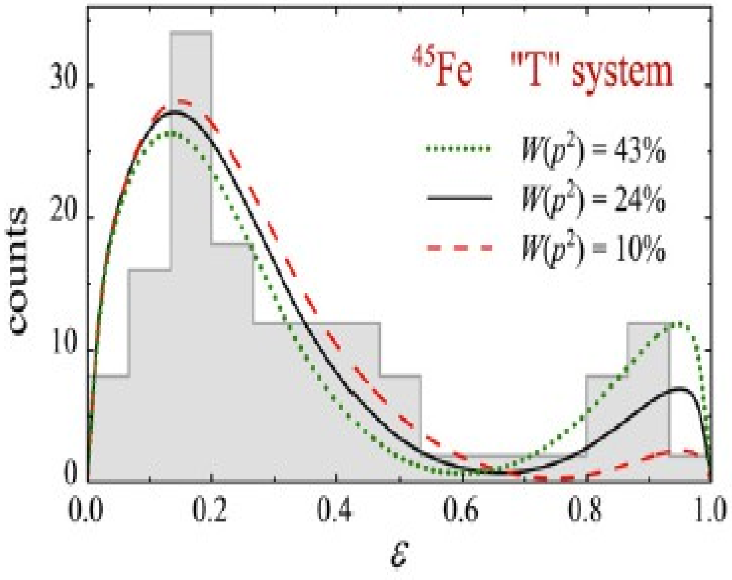


PRC 80 (2009) 024306

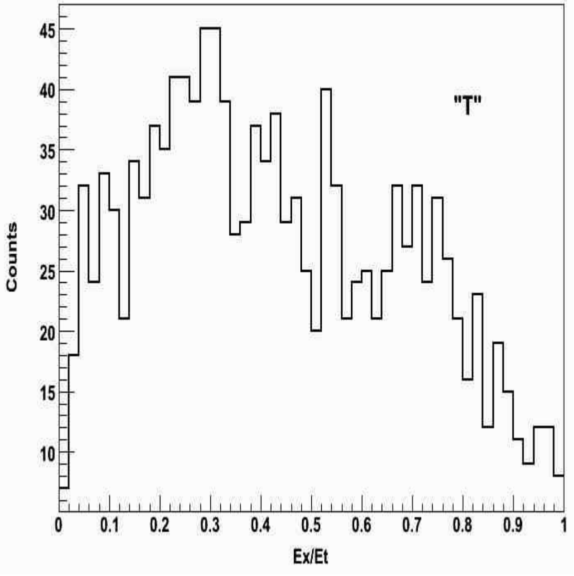


PRC 86 (2012) 011304R

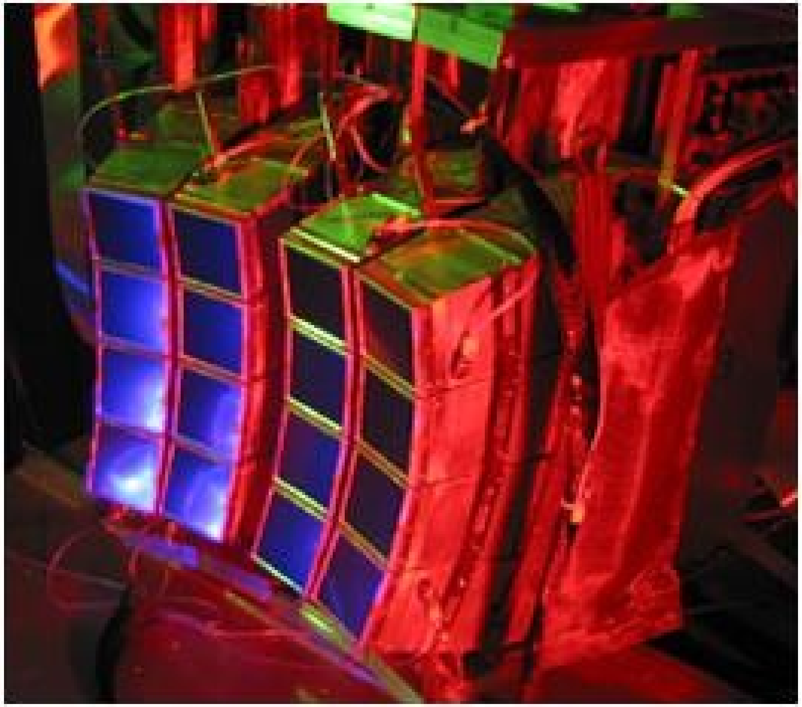




PLB 677 (2009) 30



$^{16}Ne_{gs}$



Charity,Komarov, Sobotka, Elson, Manfredi, Shane,Brown,Jager
Buhro Washington Univ.
Egorva, Grigorenko, Bogolyubov Lab. of Theoretical Phys. Dubna
Hagino, Tohoku Univ., Sagawa, Univ. of Aziu
Clifford, Bazin,Chajecki, Coupland, Gade,Iwasaki,Kilburn, Lee,
Lukyanov, Lynch, Mocko, Lobastov, Rodgers, Sanetullaev, Tsang,
Wallace, Winkelbauer, Youngs, Barney, Showalter. NSCL, Michigan State Univ.
Hudan, Metelko Indiana Univ.
Famiano, Wuosmaa, Marley, Shetty, Bedoor, McNeel, Western Michigan Univ.
McCleskey, Pizzone, Roeder, Spiridon, Simmons,Trache. Texas A&M
Kurokawa, RIKON
Van Goethem Kernfysisch Versneller Instit.
Ghosh, Variable Energy Cycoltron Centre, Kolkata Howard, Rutgers Univ.
Zhukov, Calmers Univ., Sweden

Summary

HiRA is a powerful tool for invariant mass spectroscopy

Exotic structure in light nuclei is not confined to nuclei near the drip lines (high T_z) but more generally to states with high T.

Strong connection between two-proton decay and two-neutron halo nuclei.

Two-proton decay of proton-rich members of the
A=6, T=1 triplet ^{6}Be
A=8, T=2 quintet ^{8}C and $^{8}B_{IAS}$
A=11, T=5/2 sextet $^{11}B_{DIAS}$
A=12. T=2 quintet ^{12}O and $^{12}N_{IAS}$

2*p* decay from Isobaric analog states -
new class of 2*p* decay

Correlations between the three-body decay fragments tell us if the decay is sequential or prompt. For prompt decay, we are sensitive to the relative diproton and Cigar configurations in the halo