Two-Proton Decay Experiments

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Classification of 2p decays

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

Sequential 2p decay

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

Reality can be more complex
6Be – Democratic and Goldansky?
or almost Goldansky
Barker – width of 6Be not explained by sequential 2p decay (Rmatrix)
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
\[ t_{1/2} < 10^{-20} \text{ s} \]

- \(^6\text{Be}\)
- \(^8\text{C}\)
- \(^{12}\text{O}\)
- \(^{16}\text{Ne}\)

\(^{19}\text{Mg} \ t_{1/2} = 4 \text{ ps}\)

Long lived

\[ t_{1/2} > 1 \text{ ms} \]

- \(^{45}\text{Fe}\)
- \(^{48}\text{Ni}\)
- \(^{54}\text{Zn}\)

Possible candidates

- \(^{26}\text{S}\)
- \(^{30}\text{Ar}\)
- \(^{34}\text{Ca}\)

Excited states

- \(^8\text{B}\)
- \(^{10}\text{C}\)
- \(^{18}\text{Ne}\)
- \(^{17}\text{Ne}\)
## Correlations in $2p$ decay

### Information content from n-body decay

<table>
<thead>
<tr>
<th></th>
<th>2-body</th>
<th>3-body</th>
<th>4-body</th>
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<tr>
<td>Degree of freedom*</td>
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<td>Orientation</td>
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<tr>
<td>Remaining</td>
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<td>2</td>
<td>5</td>
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</tbody>
</table>

* - ignoring spin degrees of freedom

In $\beta$ 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.

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$^{45}$Fe
Miernik et al.
Relationship to 2-neutron-halo nuclei.

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

\[ ^{6}\text{Be} - ^{6}\text{He} \]
\[ ^{8}\text{C} - ^{8}\text{He} \]
\[ ^{11}\text{O?} - ^{11}\text{Li} \]

To experimental study \textit{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-\textit{p} decay of the mirror state can be studied in one model. Turning off the Coulomb interaction in such a model will give the \textit{n-n} correlations.

Grigorenko et al PRC 80 (2009) 034602
Soft Dipole Mode in Halo Nuclei

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

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

Soft dipole in $^6\text{He}$
Nakayama PRL 85 (2000)262
HiRA array
Washington University
Michigan State,
Western Michigan
Indiana University

Low-energy configuration
\(E/A \sim 10 \text{ MeV}\)
\(\Delta E - E\) from Si(65\(\mu\))-Si(1.5 mm)
Texas A&M University \(^{10}\text{C}\) beam

High-energy configuration
\(E/A \sim 70 \text{ MeV}\)
\(E - \Delta E\) from Si(1.5 mm)-Cs(\text{Tl})
Michigan State University, \(^9\text{C}, \; ^{12}\text{Be}\) beams

1.5 mm DSSD has 32x32 strips
~800 Si strips in experiment.
Chip readout.
Multi-hit capability
$^6\text{Be}$ states

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

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

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

Correlations can not be described by sequential $p+^5\text{Li}_{\text{g.s.}}$ 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.
As the lifetime of this state is so short, do the correlations depend on the reaction.
$^8\text{C}_{\text{g.s.}}$ ground state $\Gamma=130\pm50$ keV

Cannot be reproduced with sequential calculation ($R$-matrix) through $^7\text{B}$.

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

Unstable to decay to $4p+\alpha$.

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

~2000 events detected
~2% efficiency

New measurement of mass excess and width.
Looking for $^6\text{Be}$ in $^8\text{C}$ decay.

$^6\text{Be} \rightarrow 2p+\alpha$

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

Fit $^6\text{Be}_{\text{g.s.}}$ peak $\rightarrow 1.01 \pm 0.05$ $^6\text{Be}_{\text{g.s.}}$ fragments in each $^8\text{C}_{\text{g.s.}}$ event.

All $^8\text{C}_{\text{g.s.}}$ Fragments decay through $^6\text{Be}_{\text{g.s.}}$.

Two sequential steps of 3-body decay.
$^6$Be decay after $^7$Be $n$-knockout

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

$^6$Be decay in $^8$C decay

Correlations for $^8$C → $2p + ^6$Be

Enhancement in diproton region relative to $^6$Be → $2p+\alpha$ decay.

To calculate the $2p$ decay of $^8$C, does one need to consider 5-body models.
Are there other $4p$ emitters?

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

$^{21}\text{Si} \rightarrow 2p^{19}\text{Mg} \rightarrow 4p^{17}\text{Ne}$

No estimates of their mass or width at the moment.
Could be produced in one or two-neutron knockout reactions.
$^8\text{B}$ excited state $\rightarrow 2p + ^6\text{Li}$
Proton-knockout from $^9\text{C}$ beam ($E/A=70$ MeV)

Measured $E^* = 7.05$ or $10.61$ MeV
$\Gamma < 75$ keV

No known narrow level at 7.05 MeV

$^8\text{B}_{\text{IAS}} E^*=10.619\pm0.009$ MeV, $\Gamma<60$ keV

$2p$ decay from IAS to IAS

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

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

Do the correlations between the protons give information on isospin mixing?
Are three other IAS to IAS 2p emitters? Probably $^{12}\text{N}_{\text{IAS}}$ and $^{16}\text{F}_{\text{IAS}}$
These are analogs to the $^{12}\text{O}$ and $^{16}\text{Ne}$ 2p 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

These states are expected to have strong 2-$\alpha$ cluster structure.
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?

AMD density predictions
For mirror nucleus $^{10}$Be
9.69-MeV state in $^{10}$C ($\Gamma = 490$ keV) → 2p+2$\alpha$

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

Collaborators
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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 spectostoscopic factor. (Barker and Brown) Predicts correct decay width for $^6\text{Be}, ^8\text{C}, ^{45}\text{Fe}$. Doesn't work for $^{12}\text{O}$ (experimental value wrong). However experimental correlations are not just diproton in nature.

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

Isospin considerations?