Beta decay of halos…

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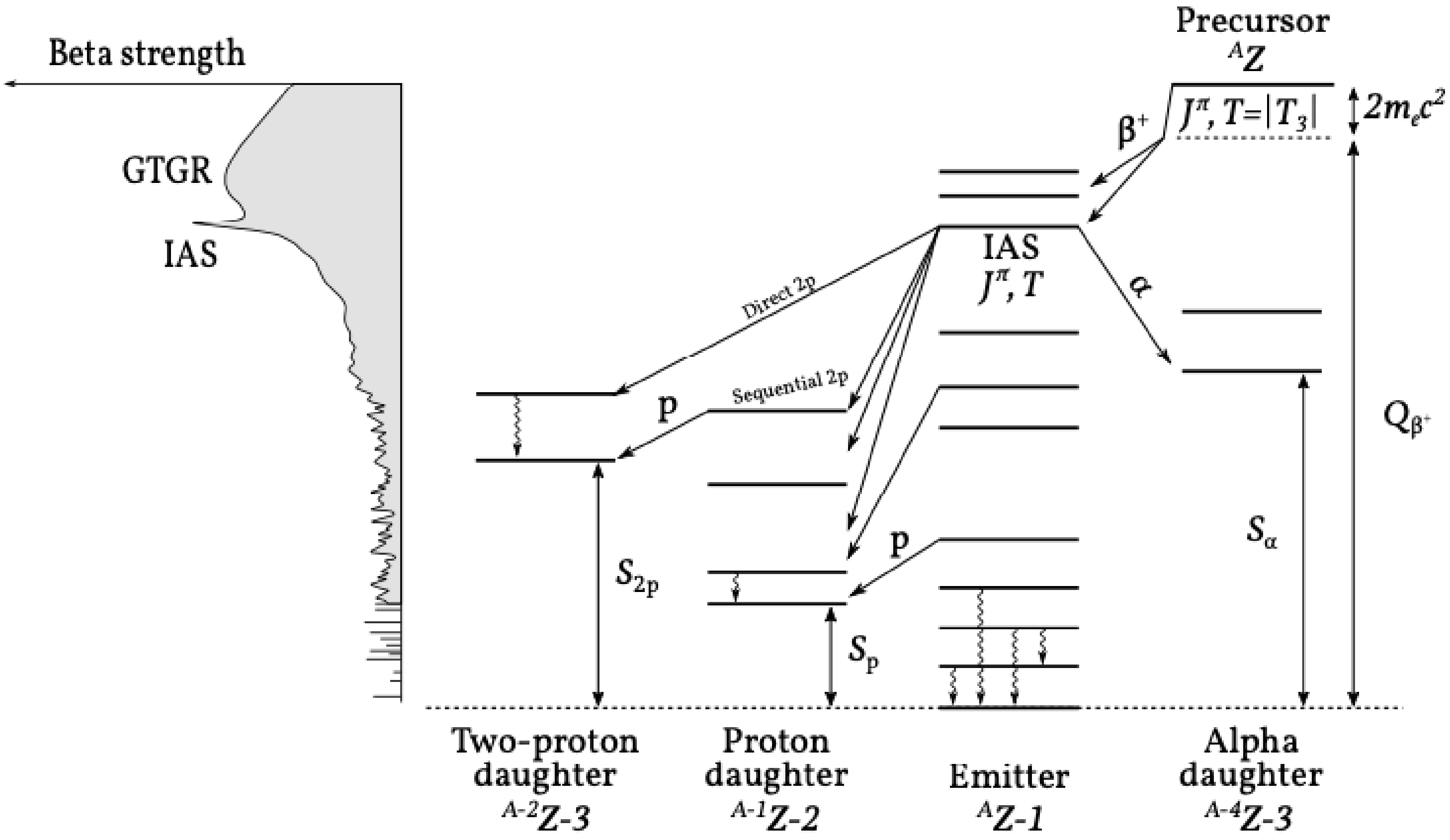
Beta decay – some observations

Rev.Mod.Phys. 84 (2012) 567

- Clean mechanism for allowed decays
- Fermi strength concentrated (IAS)
- Gamow-Teller GR

$$ft = \frac{\mathscr{T}}{B(F) + \left(\frac{g_A}{g_V}\right)^2 B(GT)}$$

$$\mathscr{T} = \ln 2 \frac{2\pi^3 \hbar (\hbar c)^6}{g_V^2 (m_e c^2)^5} = 6144(4)\mathrm{s}$$



Halo states – some properties

Rev.Mod.Phys. 76 (2004) 215

- Large spatial extension (beyond "nuclear core"), related to
  - Low separation energy (if g.s., close to driplines) and
  - Small extra-nuclear barriers (angular momentum / Coulomb)

- Clustered structure – core + halo

- Factorization in ideal cases, giving:

$$\mathcal{O}_\beta|\text{halo state}\rangle = \mathcal{O}_\beta\big(|\text{core}\rangle|\text{halo}\rangle\big) = \big(\mathcal{O}_\beta|\text{core}\rangle\big)|\text{halo}\rangle + |\text{core}\rangle\big(\mathcal{O}_\beta|\text{halo}\rangle\big)$$

… remember isospin !

- Strong isospin-isospin forces
  - …leads naturally to isobaric analogue states (and anti-analogue states)

D. Robson, Phys. Rev. 137 (1965) B535

$$
\begin{aligned}
|\mathrm{halo}\rangle &= |(t_2,t_3)t_h,t_c;T=t_h+t_c,T_z=-t_h-t_c\rangle = \\
&= |t_c,t_c^z=-t_c\rangle|t_h,t_h^z=-t_h\rangle, \qquad (2)
\end{aligned}
$$

$$
\begin{aligned}
|\mathrm{IAS}\rangle &= |(t_2,t_3)t_h,t_c;T=t_h+t_c,T_z=-t_h-t_c+1\rangle = \\
&= \sqrt{\frac{t_h}{t_c+t_h}}|t_c,t_c^z=-t_c\rangle|t_h,t_h^z=-t_h+1\rangle + \\
&+ \sqrt{\frac{t_c}{t_c+t_h}}|t_c,t_c^z=-t_c+1\rangle|t_h,t_h^z=-t_h\rangle, \qquad (3)
\end{aligned}
$$

$$
\begin{aligned}
|\mathrm{AAS}\rangle &= |(t_2,t_3)t_h,t_c;T=t_h+t_c-1,T_z=-t_h-t_c+1\rangle = \\
&= \sqrt{\frac{t_c}{t_c+t_h}}|t_c,t_c^z=-t_c\rangle|t_h,t_h^z=-t_h+1\rangle - \\
&- \sqrt{\frac{t_h}{t_c+t_h}}|t_c,t_c^z=-t_c+1\rangle|t_h,t_h^z=-t_h\rangle, \qquad (4)
\end{aligned}
$$

E. Garrido et al., Phys. Rev. C107 (2023) 014003

Isospin purity ?

- NB! Isospin mixing - distinct from “IAS non-overlap”
  - Coulomb mixing matrix elements at most around 100 keV…
  - Typically, small effects (10^{-4}), in halos of order 10^{-3} – 10^{-2}

- Larger mixing expected:
  - In the low-lying continuum e.g. Robson (1965) or Mitchell et al, RMP 82 (2010) 2845
  - (Do for halos = just below continuum)
  - At intermediate distances e.g., Garrido et al, PL B 648 (2007) 274

Halo signals in beta decays ?

Handbook of Nuclear Physics, chap 27

- Spatial extension changes overlap matrix element
  - W.r.t. to mirror systems: lower binding may change wavefct. structure…

- Imprints of the clustered structure
  - Low separation energies give new (beta-delayed) decay channels…

e.g. $Q_{\beta d}$ = 3.007 MeV-S_{2n}

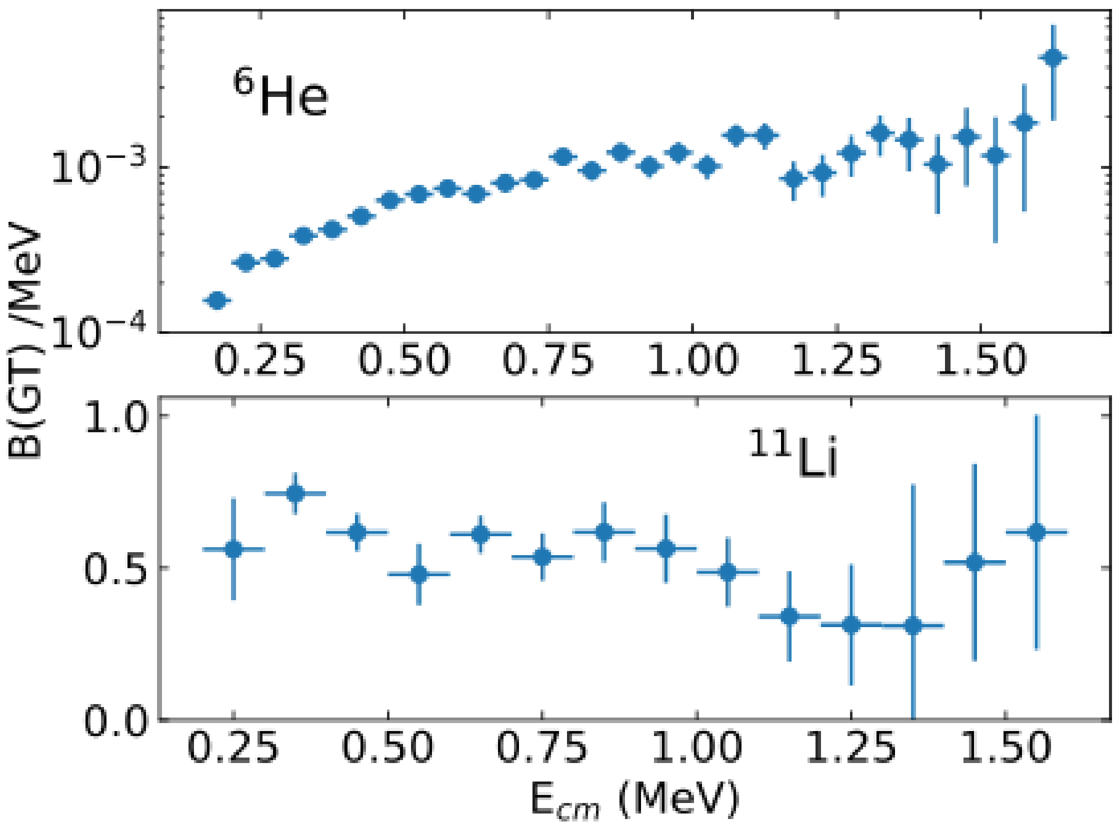
B. Jonson, KR, NP A 693 (2001) 77

- Different decay dynamics - decays directly to continuum…

- The obvious example: beta-delayed deuteron emission

Two beta-d cases: ^{6}He and ^{11}Li

Phys. Rev. C 92 (2015) 014316



Phys. Rev. Lett. 101 (2008) 212501

- ^{6}He:
  - g.s. in ^{6}Li has alpha-d structure
  - significant cancellation for the continuum part
- ^{11}Li:
  - clearly continuum spectrum
  - theory difficult (but seems ok)

Here: beta strength extracted bin by bin NP A 925 (2014) 112

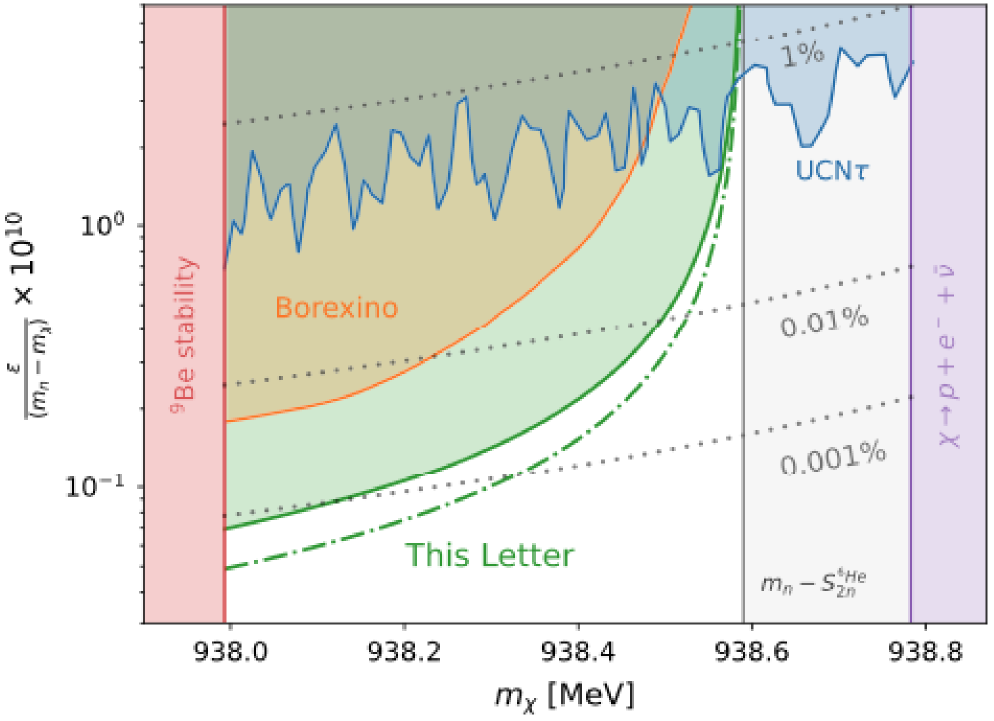
Intermezzo: dark decays

Fornal and Grinstein, PRL 120 (2018) 191801

- Idea – inconsistencies in n decay due to small “n to X” branch ?
- Free neutron or neutrons in n-halo nuclei

PR C97 (2018) 042501

- Recent impressive limits from ^{6}He exp at GANIL



PHYSICAL REVIEW LETTERS **132**, 132501 (2024)

Search for a Neutron Dark Decay in ^{6}He

M. Le Joubioux,[1,*] H. Savajols,[1,†] W. Mittig,[2,3] X. Fléchard,[4] L. Hayen,[4,5] Yu. E. Penionzhkevich,[6,7] D. Ackermann,[1] C. Borcea,[8] L. Caceres,[1] P. Delahaye,[1] F. Didierjean,[9] S. Franchoo,[10] A. Grillet,[9] B. Jacquot,[1] M. Lebois,[10] X. Ledoux,[1] N. Lecesne,[1] E. Liénard,[4] S. Lukyanov,[6] O. Naviliat-Cuncic,[2,3,4] J. Piot,[1] A. Singh,[1] V. Smirnov,[6] C. Stodel,[1] D. Testov,[11,12] D. Thisse,[10] J. C. Thomas,[1] and D. Verney[10]
[1]*Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DRF-CNRS/IN2P3.*

What about beta-delayed p emission ?

- A halo decay case: ^{11}Be
  - Final state p + ^{10}Be, focus here on its branching ratio
  - A series of attempts to detect ^{10}Be gave upper limit 2.2 10^{-6} — EPJ A (2020) 56:100
  - Positive identification of p in active target exp, 8.0 10^{-6} — PRL 123 (2019) 082501
  - As yet unpublished upper limit 2 10^{-6} with optical TPC — N. Skolowska et al

  - Too many calculations to list – could have 1/2^{+} **and** 3/2^{+} levels nearby
  - New observations of a near-threshold level — PRL 129 (2022) 012501; ibid 012502

- A “core decay” case: ^{8}B
  - Expect a branching ratio of 2 10^{-8}, current limit 2.6 10^{-5}… — J.Phys. G 40 (2013) 035109

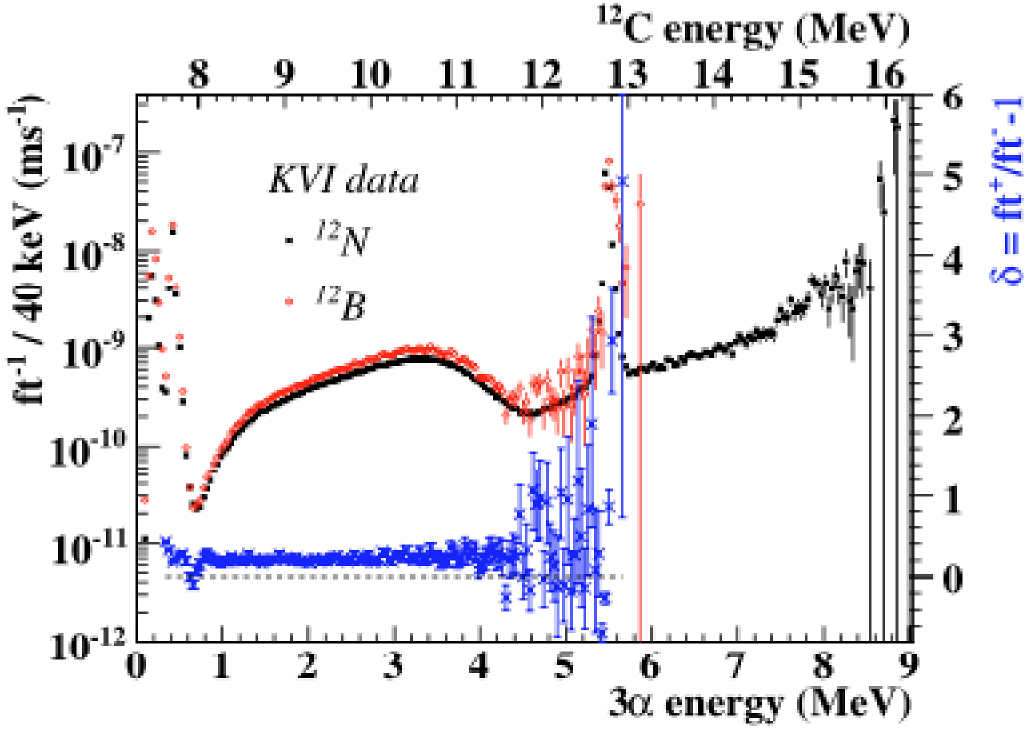
Continuum decays for ^{8}B and ^{12}N ?

- ^{8}B decay about 10% slower than ^{8}Li decay

Wilkinson and Alburger, PRL 26 (1971) 1127

- ^{12}N decay also slower than ^{12}B decay:

PL B 678 (2009) 459



- Evidence for decays to continuum ?

NP A 940 (2015) 119

Proton halos – beta asymmetry as probe

Eur. Phys. J. A (2023) 59:35

- First attempt, ^{17}Ne (to 1st excited state ^{17}F)
  - Exp: first forbidden, twice that of ^{17}N – Theory: radial extension/occupations ??

N. Michel et al., NP A 703 (2002) 202

- Second case, ^{26}P (to several states in ^{26}Si)
  - Exp: varies (1st ex: 0.6 that of ^{26}Na) – Theory: shell model may give this, systematics ??

D. Pérez-Loureiro et al., PR C 93 (2016) 064320

- Third case, ^{22}Al* (^{22}Si into 1st 1^{+} state)
  - Exp: 0.3 that of ^{22}F – Shell-model: due to too little d-wave (more s-wave) configuration…

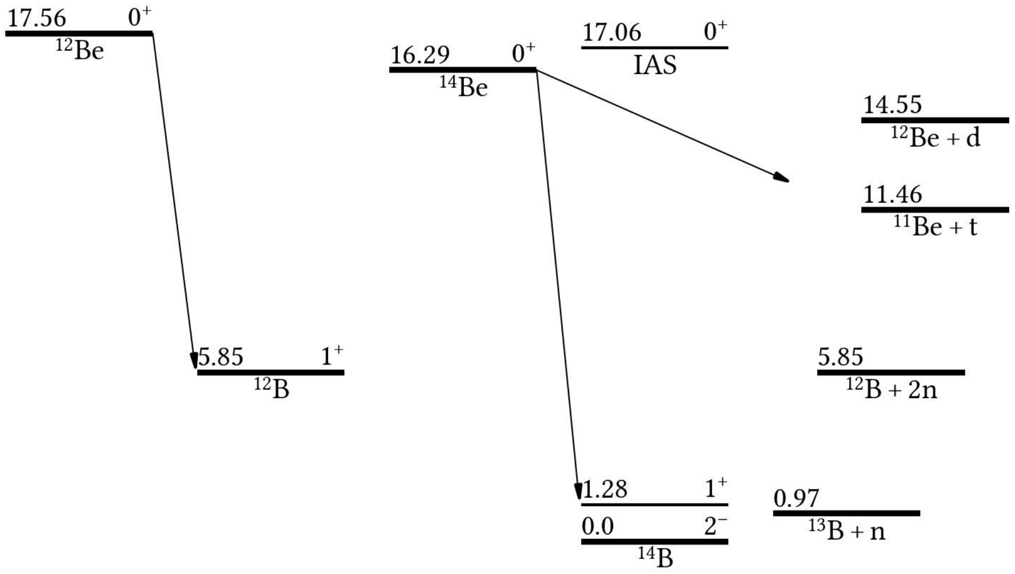
J. Lee et al., PRL 125 (2020) 192503

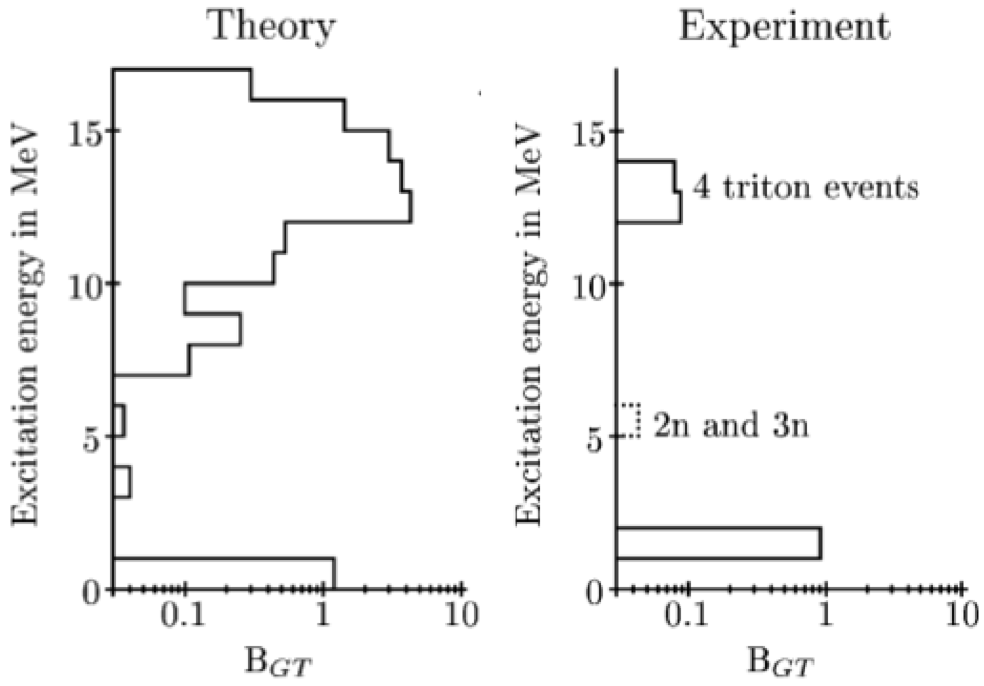
- Need more theory to obtain solid conclusions!

The puzzle of ^{14}Be

- Why so simple ? Only core decay ??

H. Jeppesen et al.,
N.P. A 709 (2002) 119

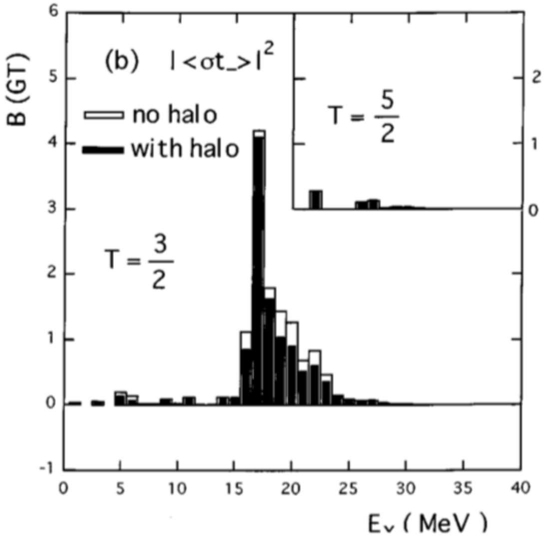




More detailed look at ^{11}Li

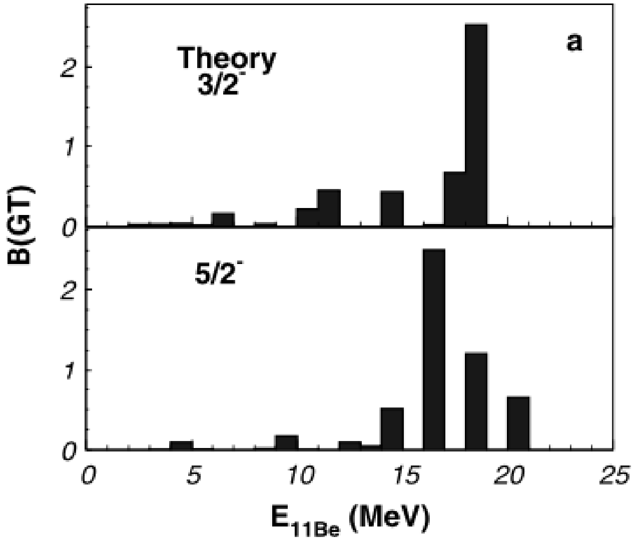
- Clear halo state, complex decay, Q_β = 20.55 MeV
- Branches (%): 1n - 86.3(9), 2n - 4.1(4), 3n - 1.9(2), α - 1.7(3), d+t - 10^{-2}
- Most experiments go up to 8-10 MeV, but do not agree internally
- Shell model:

e.g. $p_{1/2}$ to $p_{3/2}$ feeding low-lying $1/2^-$



T. Suzuki, T. Otsuka
PR C56, 847

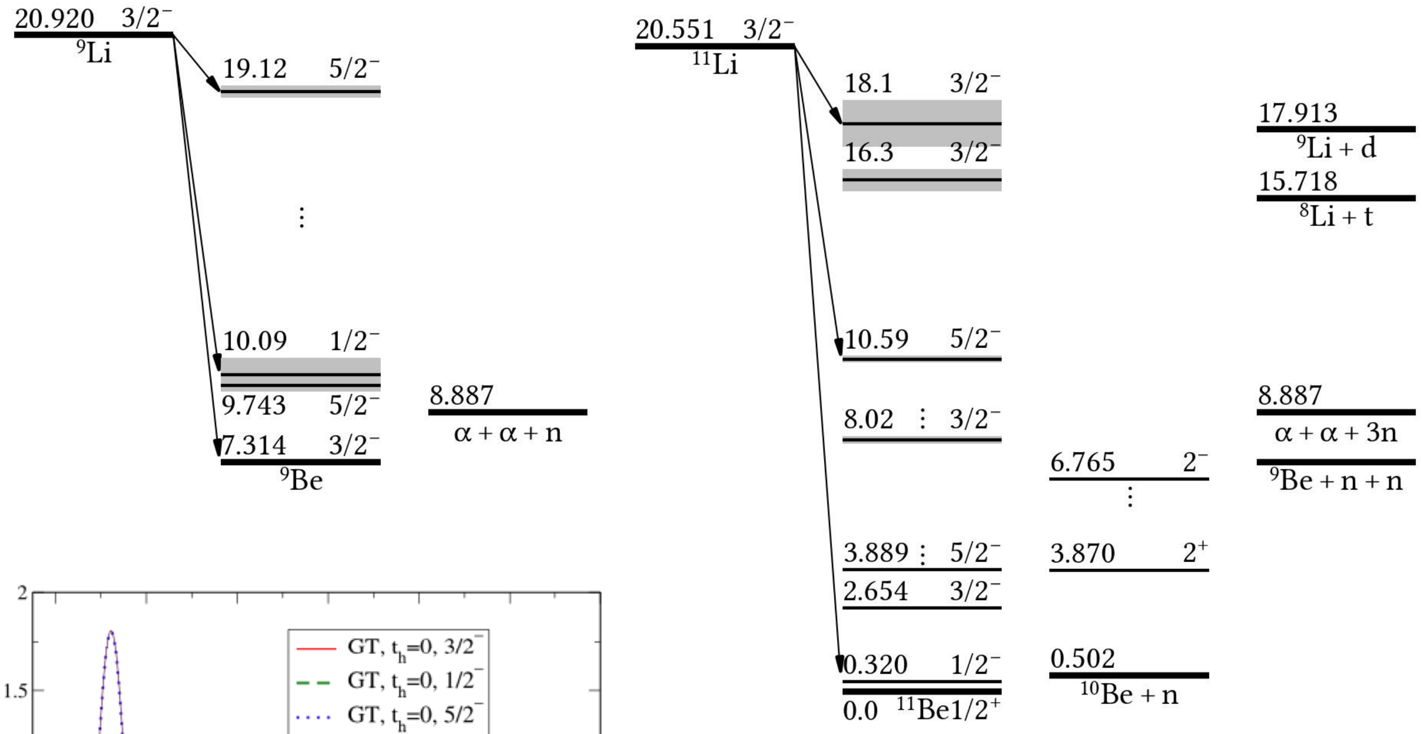
M. Madurga et al.,
PL B677, 255

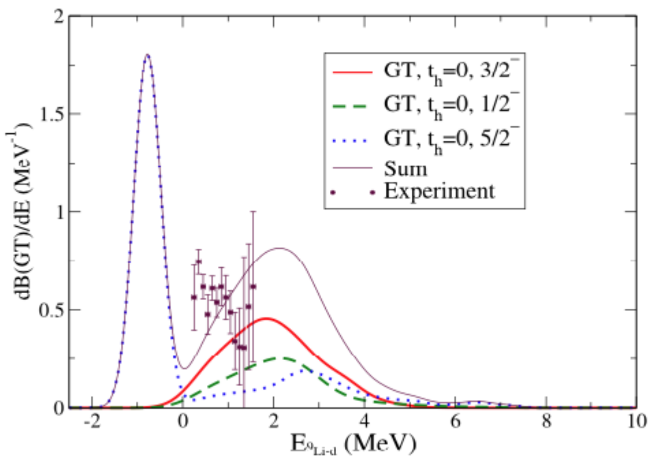


Three-body model with explicit isospin

Adjust core-n potentials to exp data

E. Garrido et al., Phys. Rev. C107 (2023) 014003

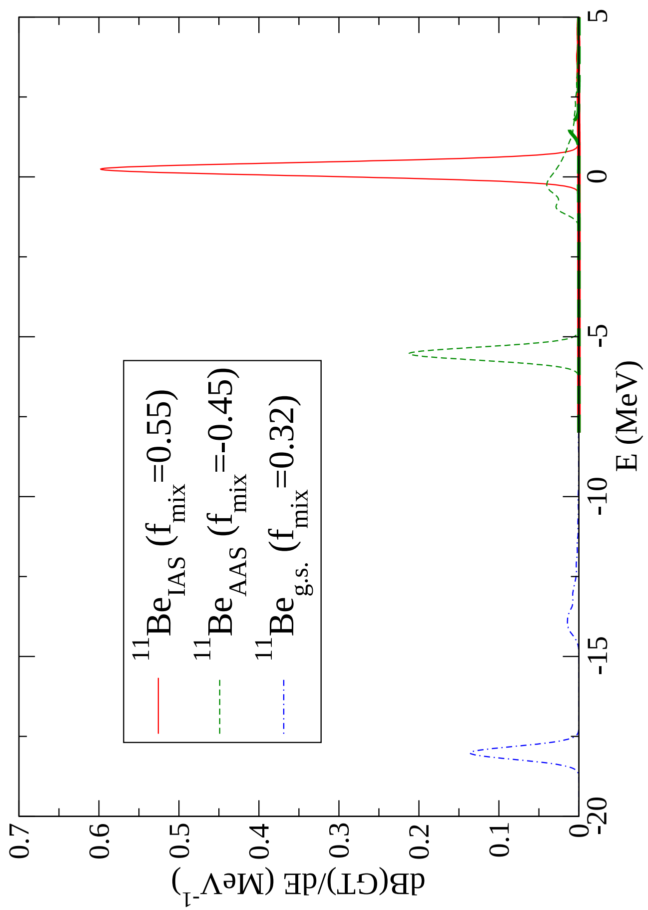




$t_h = 0$

Miss: core-decays to excited states and $p_{1/2}$ to $p_{3/2}$…

$t_h = 1$



IAS

AAS

$^{9}Be_{gs}$

Theory GT strength

Quantum numbers as:

Not yet there: decay of hypernuclei

- Expect hypertriton to be Lambda loosely bound to deuteron…

- Many recent experiments (ALICE, STAR…)
  - Lifetime – modified from free Lambda lifetime ?
  - Binding energy – around 100-200 keV
  - Weak decay branching ratios – few measurements…

- "Classic" halo observables ?
  - Electromagnetic response
  - Interaction radius

C.A. Bertulani, Phys.Lett. B 837 (2023) 137639

Conclusions

- Beta decays directly to continuum states occur for halos
  - Clearly for beta-d decays, potentially more general
  - Neutron halos: multi-particle continuum (difficult experiments)

- Decay patterns may reflect the halo structure

- Mirror asymmetry not yet quantitative indicator

- Wanted: Theory that handles continuum and isospin correctly

Thanks to:

MAGISOL

and the many students that have spent time in the group !

Theory colleagues (D.V. Fedorov, E. Garrido, A.S. Jensen…)

My Danish funders (NICE, DFF…)

Decay scheme for ^{11}Li

Low E: 1n (+ γ) channel

C. M. MATTOON *et al.* PHYSICAL REVIEW C **80**, 034318 (2009)

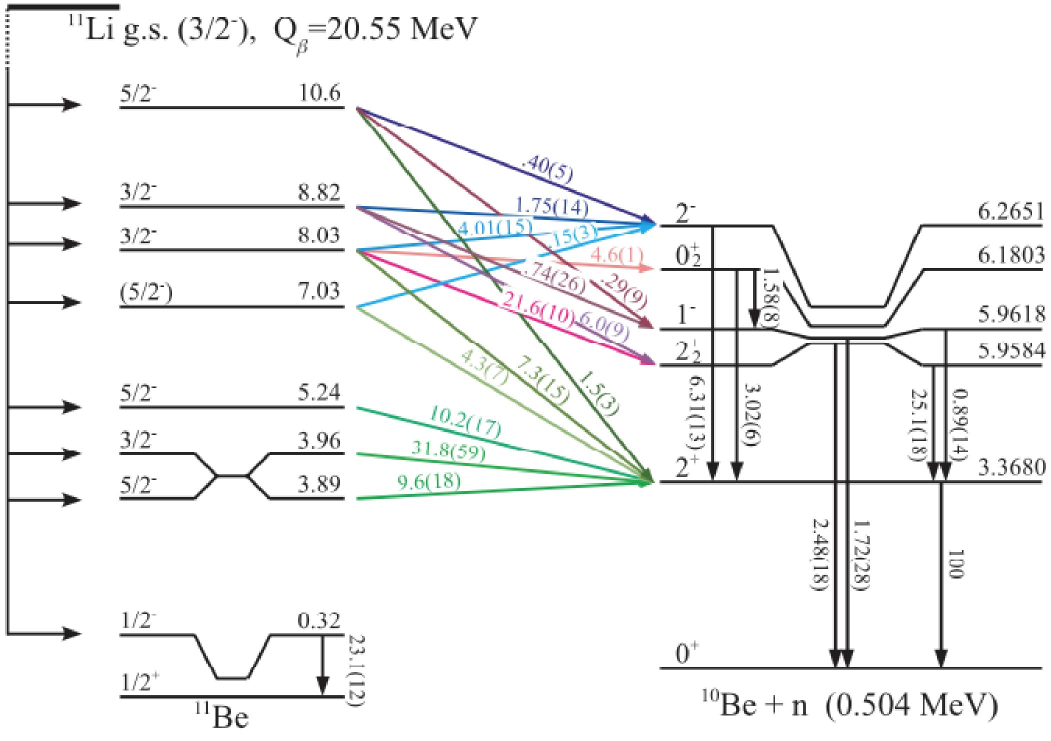
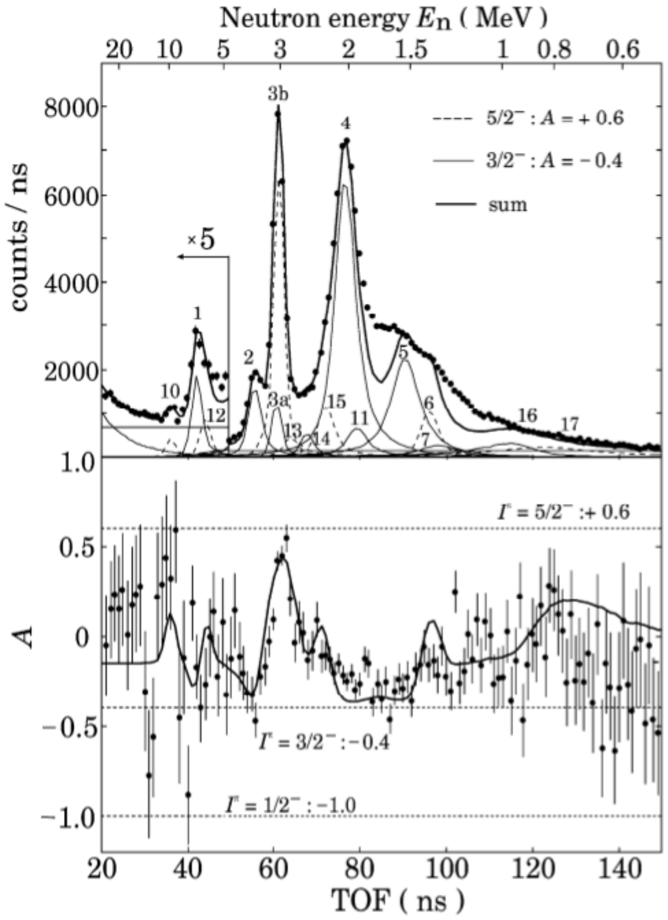
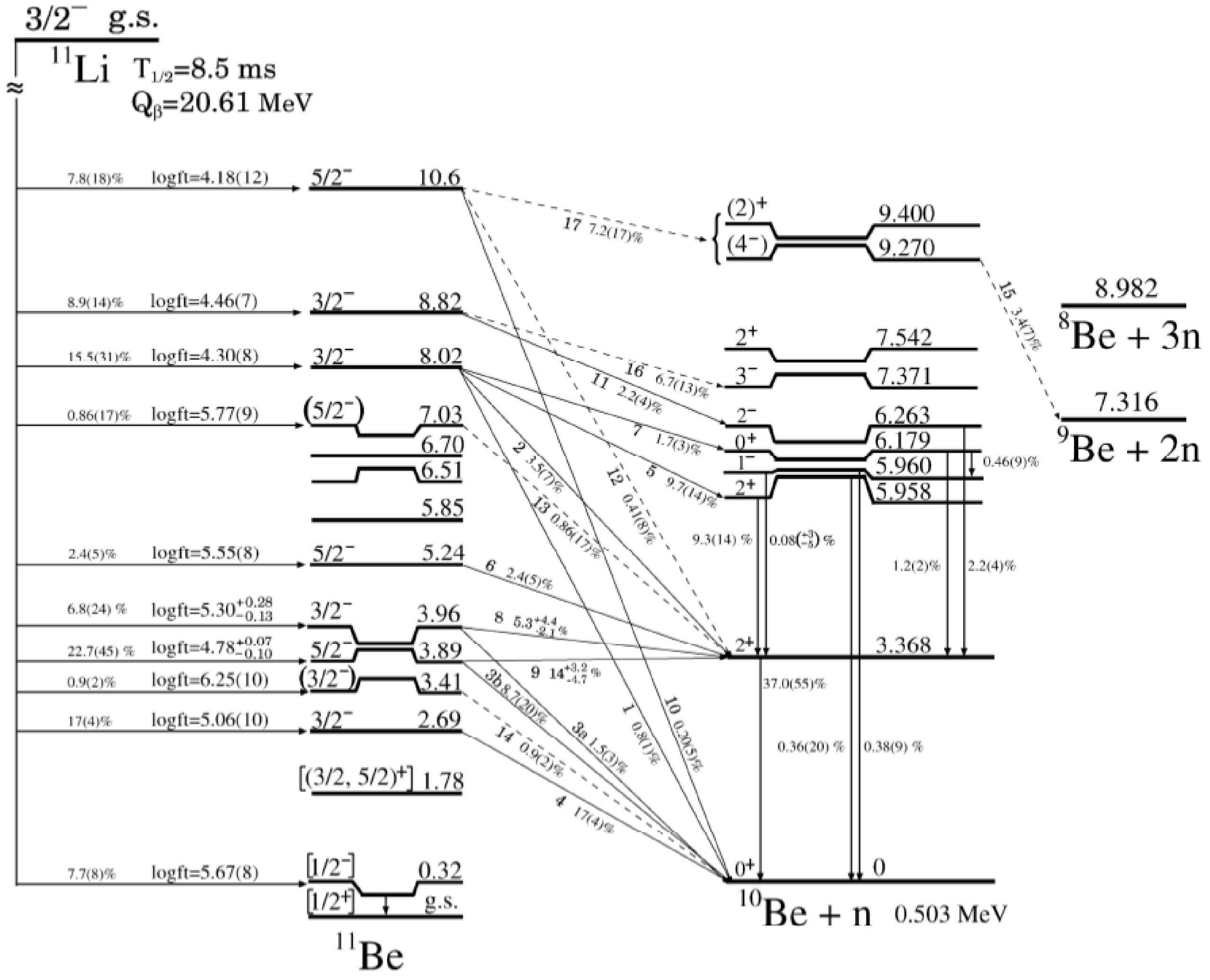


FIG. 15. (Color online) β-delayed one-neutron emission decay scheme of ^{11}Li extracted from this experiment. Intensities given are relative to the intensity of the $2_1^+ \rightarrow 0_1^+$ transition (100). The color scheme refers to the colors used to identify the neutron branches in the figures presenting the line-shape analyses.

Y. Hirayama et al., Phys. Lett. B611 (2005) 239





The beta-2n and -3n branches

- $P_n = \Sigma\, iP_{in} = 100.3(1.4)$ %
  - $P_{1n} = 86.3(9)$ %
  - $P_{2n} = 4.1(4)$ %
  - $P_{3n} = 1.9(2)$ %
  - 14% of n's from 2n/3n
  - Multiplicity 2: more 3n than 2n

- IS525, Delauny et al

  arXiv:1906.04699

  Il Nuovo Cimento 42 C (2019) 98

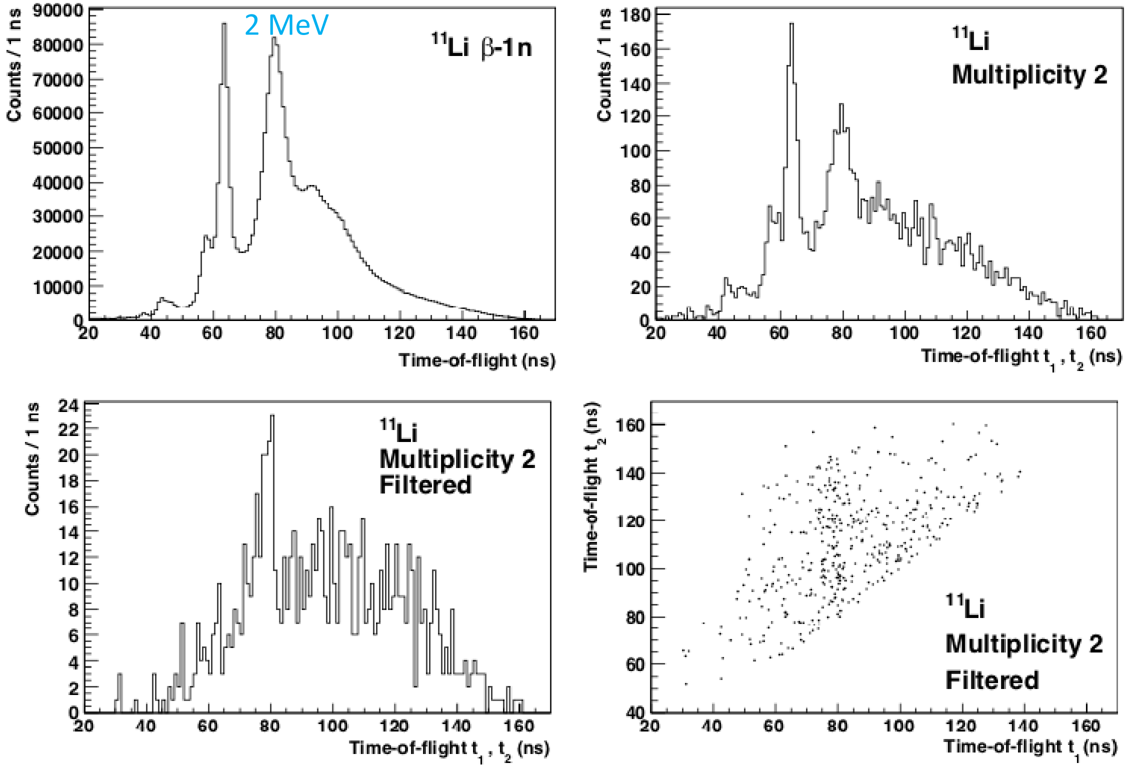


Fig. 1. – Time-of-flight spectra of ^{11}Li β-delayed neutrons detected in the near array. Top left: single neutron events. Top right: Multiplicity-2 events before cross-talk rejection. Bottom left: Multiplicity-2 events after cross-talk rejection. Bottom right: Time-of-flight of the second hit t_2 *vs.* time-of-flight of the first hit t_1, after cross-talk rejection.

M. Madurga et al., Nucl. Phys. A810 (2008) 1

Table 3
Branching ratios for channels determined in this work following ^{11}Li β-decay. The total branching ratio to charged particle emitting channels obtained in [2] is 3.1(9)%, compared to the value of 1.73(2)% in this work. The ^{11}Li activity was deduced from the branching of the β-(^{7}Li + α) decay channel of the daughter

Channel	β-feeding (%)[a]	β-feeding (%)[b]	β-feeding (%)[c]
^{11}Be(10.59) $\rightarrow$ n + ^{10}Be(9.5) $\rightarrow$ 2α + 3n	1.08(2)	1.1(2)	1.4(2)
^{11}Be(10.59) $\rightarrow$ n + ^{10}Be(9.5) $\rightarrow$ n + α + ^{6}He	0.227(5)	0.23(4)	0.29(4)
^{11}Be(10.59) $\rightarrow$ α + ^{7}He $\rightarrow$ n + α + ^{6}He	0.0348(5)	0.035(6)	0.044(7)
^{11}Be(18.15) $\rightarrow$ ^{6}He(2$^+$) + ^{5}He $\rightarrow$ 2α + 3n	0.337(7)	0.34(5)	0.43(7)
^{11}Be(18.15) $\rightarrow$ α + ^{7}He $\rightarrow$ n + α + ^{6}He	0.057(1)	0.057(9)	0.072(10)

[a] Only the statistical error is consider in this column.
[b] Including the normalization uncertainty.
[c] Assuming a 2% feeding to the ground state in ^{11}Be, stated as upper limit in previous works [25].

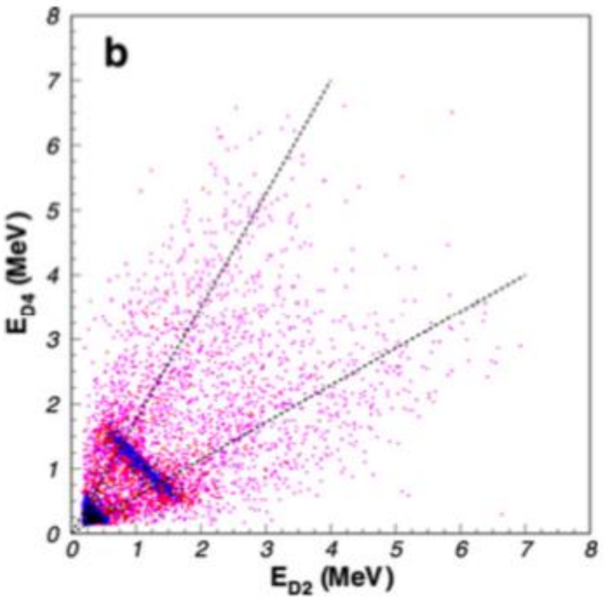


Fig. 3. Left: The energy sum of ^{11}Li β-delayed coincidence spectrum collected during the first 40 ms after the proton impact. The dashed histogram is the result of a Monte Carlo simulation of the charged particle decay channels as described in the literature [2,8]. The inset shows the same sum energy spectrum for a longer time window (t < 200 ms). The peak appearing at 1.2 MeV, indicated by an arrow, corresponds to the break-up into ^{7}Li + α of the 9.88 MeV state in the granddaughter ^{11}B. Right: (b) shows the energy-vs-energy scatter plot for charged particle coincidences between the D2 and D4 opposite detectors for t < 40 ms. The major features of the plot are the intensity at low energy and the transverse line (corresponding to peaks at 0.7 and 2.2 MeV in figure (a)). The scatter events at high energy form two lobes (at around 30 and 60 degrees).