Complementary probes of the nuclear continuum

Karsten Riisager

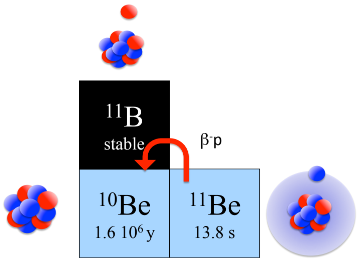
Aarhus University

March 8, 2018

Overview of talk

Resonances

Beta decay



Halos

Examples ^{10}Li, ^{11}Be, ^{8}B

Resonance characteristics

Classical concept from mechanics, electrical circuits . . .

Here: quantum mechanical system in the continuum

- Wavefunction amplitude inside/outside nucleus
- Time delay between incoming/outgoing wave packets
- Breit-Wigner energy distribution
- Complex eigen-energy $E_0 + i\Gamma/2$
- Pole in S-matrix

All of these become problematic (at least when we wish to relate the concept to experimental data) when resonances become broader

A schematic model

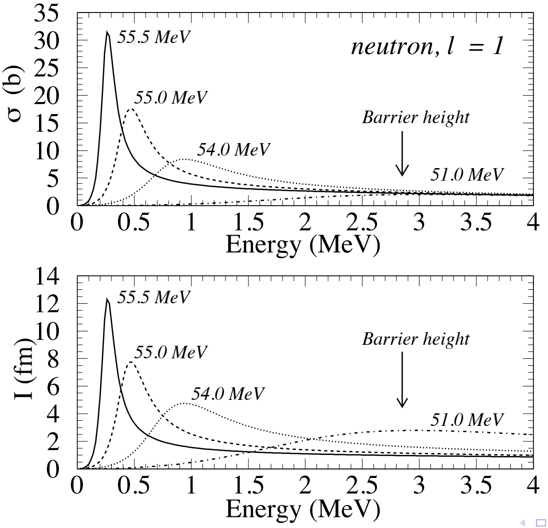
p-wave neutrons in square well potential (radius a)

Simple system displaying resonances, almost analytical ($j_\ell(kr)$, $y_\ell(kr)$)
Easy to find phase shift δ_ℓ, this gives elastic scattering cross section

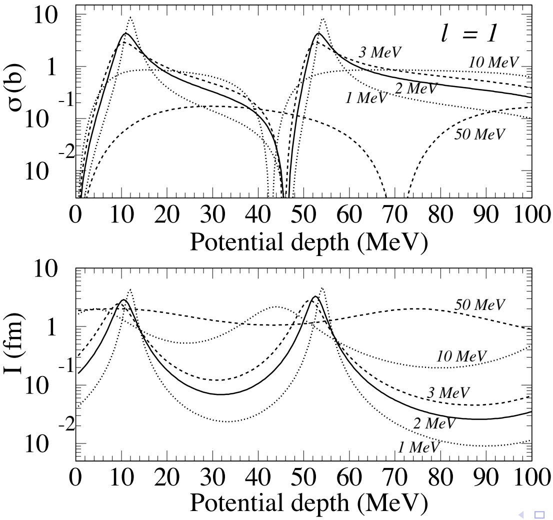
Chose wavefunction normalization as $\sin(kr + \delta_\ell - \ell\pi/2)/r$ for large radii r

For comparison, look also at integral $I = \int_0^a |R(r)|^2 r^2 \mathrm{d}r$

Elastic scattering vs. overlap



Elastic scattering vs. overlap



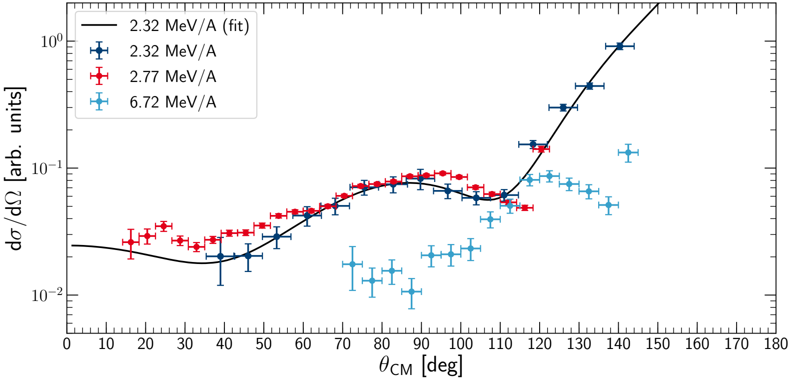
Resonance position

Different ways to define the position of a resonance

- The maximum elastic cross section
- The maximum of I (essentially identical to σ_{el})
- Phase shift passes $\pi/2$ ($|e^{2i\delta_\ell} - 1|$ maximal)
- R-matrix: $E_0 + \Delta - E = 0$, or (equivalently) δ_R through $\pi/2$ where $\delta_\ell = \phi_\ell + \delta_R$, ϕ_ℓ hard sphere phase shift
- Maximum in other observables - transfer cross section, beta-delayed particle spectrum ...

The broader the resonance, the larger the discrepancy in definitions

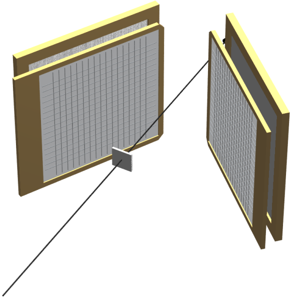
^{9}Li elastic scattering on d

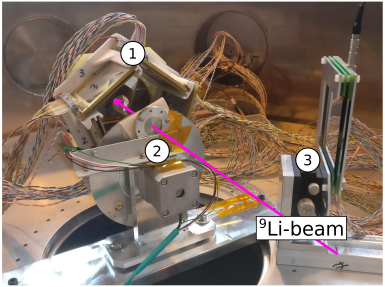


Jesper H Jensen

^{9}Li set-ups at REX/HIE-ISOLDE

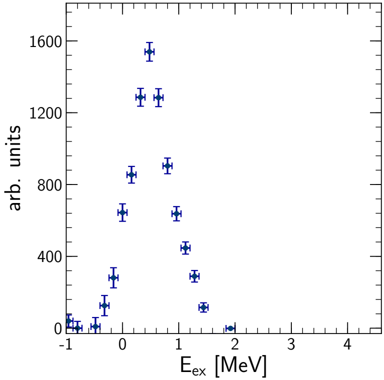
IS367 at 2.77 MeV/u and **IS561** at 6.72 MeV/u

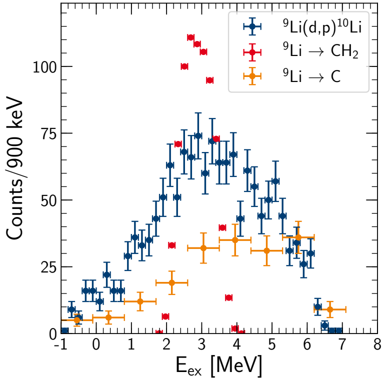




^{9}Li(d,p)

Comparing data at 2.77 MeV/u and 6.72 MeV/u





Reminder on beta-decay

β^- decay: $^AZ \rightarrow ^A(Z+1) + e^- + \bar{\nu_e}$

Two categories, Fermi and Gamow-Teller

type	$S_{e\nu}$	main strength	sum rule
F	0	IAS	$\sum B_F = \|Z-N\|$
GT	1	GTGR	$\sum B_{GT} = 3\|N-Z\|$

For neutron-rich nuclei: only expect Gamow-Teller transitions

Beta strength in the continuum

Several earlier definitions, not internally consistent.
For broad resonances: R-matrix parameter squared (a la Γ), but for interfering levels no direct coupling to spectra.

Studies of sum rules by Bergman Phys Lett B44 (1973) 23 and Romo Nucl Phys A237 (1975) 275: will work with pure continuum and can be reformulated to include resonances.

This implies the GT sum rule remains valid with a continuum formulation:

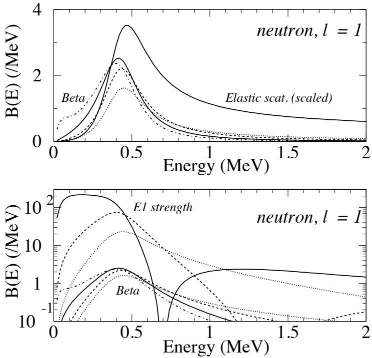
$$w(E)\mathrm{d}E = \ln 2 \frac{g_A^2}{K} f(Q-E) B_{GT}(E) \mathrm{d}E$$

Also makes life easier for the experimentalist. . .

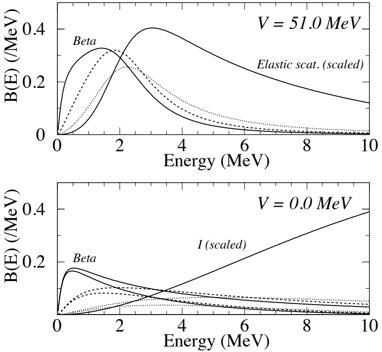
(Broad) resonances and beta-decay

Continue with the schematic model and "beta decay in the core", i.e. simple overlap of neutron initial and final wavefunctions

- Initial p-wave halo neutron
- Binding energy 5, 1, 0.2, 0.02 MeV (dot, dash, solid, dash-dot)
- Final state p-wave neutron
- Square well, calculate also scattering + E1-strength
- The "resonance" changes shape and position



More extreme conditions:



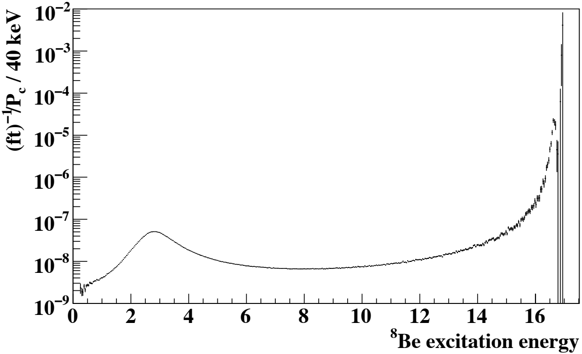
Contributions from extra-nuclear distances affect the shape.

Could be interpreted as decay directly to continuum states.

In general both direct and resonant contributions. Not wise to attempt a separation of the two.

E1-strength: similar, but more extreme.

Results for ^{8}B beta decay

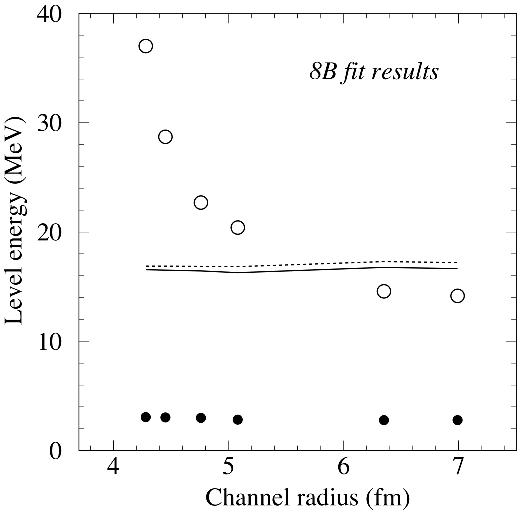


$^8\text{B} \xrightarrow{\beta} {}^8\text{Be}^* \rightarrow 2\alpha$, corrected for beta phase space and penetrability factor

Results for ^{8}B beta decay

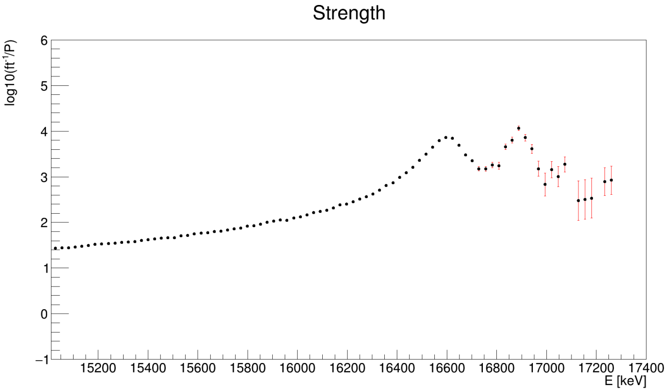
Previously established levels are stable.
"Intruder" decreases strongly with channel radius.

Decays directly to continuum ?
^{8}Be(2^+) changing structure ?



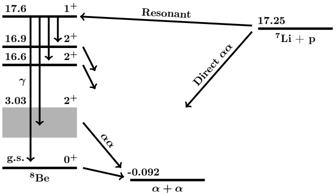
2017 ^{8}B decay experiment

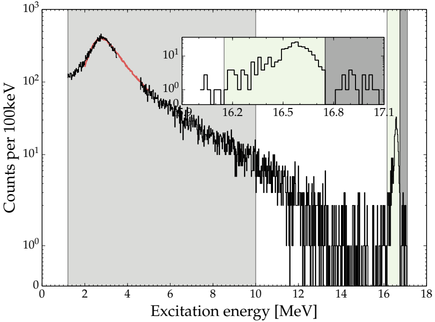
16.6 + 16.9 MeV doublet



A Gad and S Vinals

2018: ^{8}Be fed via gammas

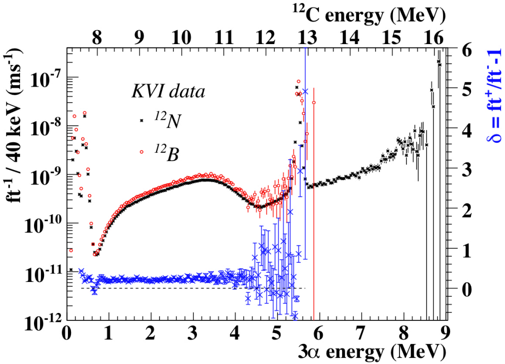




M Munch et al., submitted - ^{7}Li(p,γ)$\alpha\alpha$
arXiv:1802.10404

Results for ^{12}N beta decay

Also effects in ^{12}N decay:
Unphysical parameters if upper end is described with resonances.
Similar effects seen in the model case.



S. Hyldegaard

Summary of main halo features

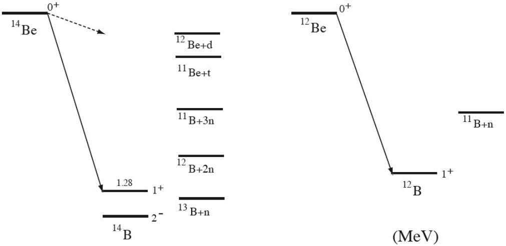
Adhere to: A.S. Jensen et al., Rev. Mod. Phys. 76 (2004) 215
Overview in: K. Riisager, Phys. Scr. T152 (2013) 014001

- Quantum system ! Tunneling into classically forbidden regions
- "Single-particle behaviour" $\Rightarrow$ require clustering
- "Large" system – tunneling out of short-range potential
- In nuclei: mainly one- and two-neutron ground state halos
- Example 1n halos: ^{11}Be, ^{15,19}C, ^{31}Ne
- Example 2n halos: ^{6}He, ^{11}Li, ^{14}Be, ^{22}C

Also: I. Tanihata et al., Prog. Part. Nucl. Phys. 68 (2013) 215
T. Frederico et al., Prog. Part. Nucl. Phys. 67 (2012) 939

Halo signatures in beta decay

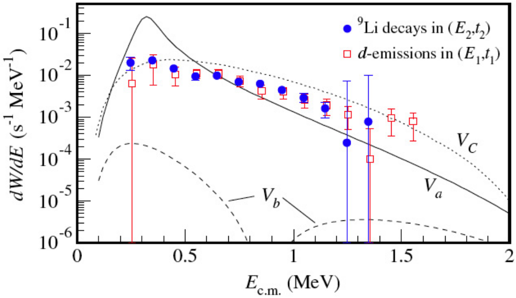
- Change in spatial overlap — moderate effect
- $\mathcal{O} \mid c+h\rangle = (\mathcal{O} \mid c\rangle) \mid h\rangle + \mid c\rangle(\mathcal{O} \mid h\rangle)$
- Decoupling of halo and core decays ?
  - Isospin symmetry ?
  - βd, βp . . .
  - ^{14,12}Be:



- Useful spectroscopic information on halo composition, ^{11}Li

Beta-delayed deuteron emission – ^{11}Li

Halo specific decay mode - seen in ^{6}He and ^{11}Li
Decays directly to continuum

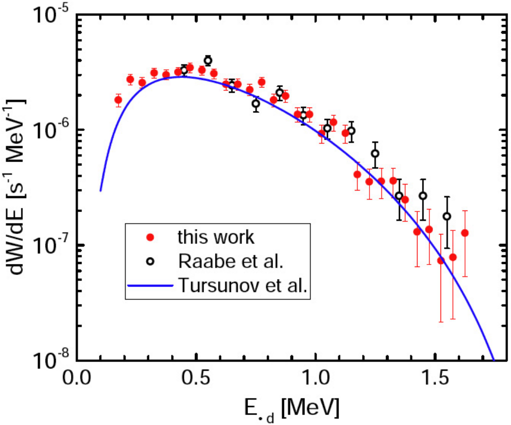


R. Raabe et al., PRL 101 (08) 212501

Potential model calculations by Zhukov et al., PR C52 (95) 2461 (V_C, only Coulomb) and Baye et al., PR C74 (06) 064302 (V_a, V_b)

...and for ^{6}He

Several experiments, the latest with an OTPC:



M. Pfützner et al., PR C92 (15) 014316
Tursunov, Baye, Descouvemont, PR C97 (18) 014302

What about ^{11}Be(βp) ?

One-neutron system simpler to interpret than two-neutron system.
However $Q_{\beta p} = 782$ keV $-S_n$ vs $Q_{\beta d} = 3007$ keV $-S_{2n}$!

^{11}Be the most favourable case Baye + Tursunov, PL B696 (11) 464
with expected branching ratio 3.0×10^{-8} (F + GT)

Emitted protons have energy below 255 keV → detect daughter nucleus ^{10}Be with halflife 1.5 My ?

Detection via Accelerator Mass Spectroscopy . . .

What about non-β ^{11}Be decay ?

Bartosz Fornal and Benjamin Grinstein (arXiv:1801.01124):
Neutron decay to dark matter particle ?
(Different lifetime for neutron disappearence and proton appearence.)

Could also happen in nuclei with low separation energy
Marek Pfützner: ^{11}Be the most favourable case (arXiv:1803.01334)

Must compare rates for proton and ^{10}Be production

Proton detection via Warsaw optical TPC

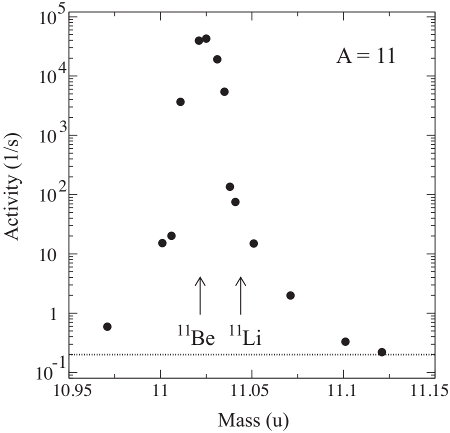
Three attempts

All collections of ^{11}Be done at the ISOLDE facility at CERN.

- September 2001, $5.2(3) \times 10^{11}$ atoms, AMS at Uppsala, "upper limit" of $2.5(2.5) \times 10^{-6}$
  M.J.G. Borge et al., J. Phys. G40 (2013) 035109
- December 2012, 3 samples, $1.47(14) \times 10^{12}$ atoms, AMS at VERA, observation $\mathbf{8.3(9) \times 10^{-6}}$
  K.R. et al., Phys. Lett. B732 (2014) 305
- May 2015, 12 samples, up to $2.98(27) \times 10^{11}$ atoms, AMS at VERA
  preliminary: slightly inconsistent branching ratio

Experimental details

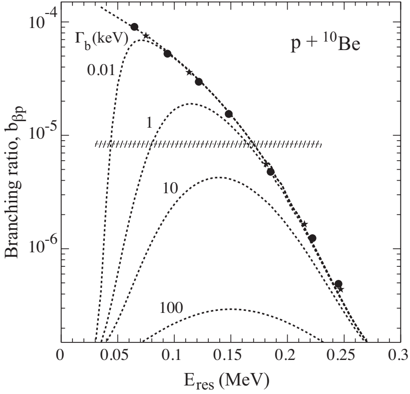
- Signal appears on ^{11}Be mass
- Surpress ^{11}Li contamination
- Signal only with laser ionization (no BeH)
- Normalize via ^{11}Be decay γ-rays



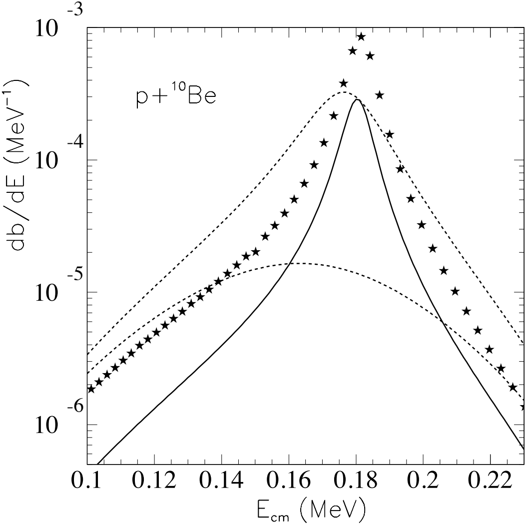
Branching ratio in simple model

Simple model:

- Detached decay of halo neutron
- Simple potential (square well/Woods-Saxon)
- Discretized final state (radius 1000 fm)
- Need "resonance" to reproduce strength



Results of the different models

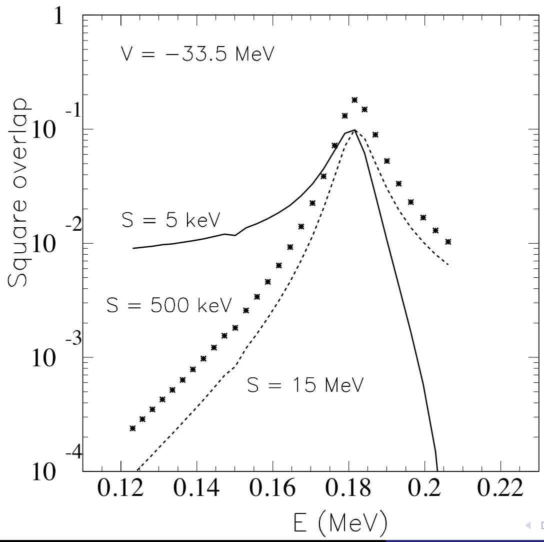


Stars: simple model

Curves: R-matrix (full) - displaced

Breit-Wigner with alpha-decay width 0 keV and 100 keV (dashed)

Dependence on halo binding energy



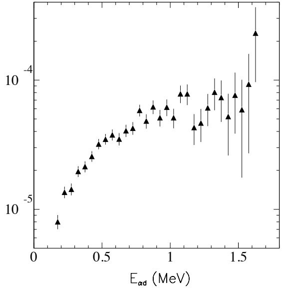
Beta strength in halo decays

Following the earlier definition:

$$w(E)\mathrm{d}E = \ln 2 \frac{g_A^2}{K} f(Q-E) B_{GT}(E) \mathrm{d}E$$

Summed observed beta strength

- For ^{6}He: 0.0016 in 1 MeV → see figure
- For ^{11}Li: 0.75 in 1.5 MeV
- For ^{11}Be: of order 1 within 0.25 MeV



Final comments

- Limitations to the resonance concept...
- Beta strength in continuum – new definition
- Expect beta decay directly to continuum (at low binding)
- Indications for separate beta decays of core and halo
- Surprisingly strong beta strength for ^{11}Be(βp), indication of a (so far unseen) resonance ? - or dark decay ?
- For experimentalists: Cannot always trust R-matrix !

^{8}B(βp) ? Would be "core decay", expect branching ratio 2.3×10^{-8}

Thanks to coworkers:

MAGISOL collaboration + Aksel S. Jensen

Some references

- M.J.G. Borge et al., J. Phys. G40 (2013) 035109 – ^{11}Be
- K.R., Nucl. Phys. A 925 (2014) 112 + Corrigendum N.P.A 925 (2014) 298 – beta strength
- K.R., H.O.U. Fynbo, S. Hyldegaard, A.S. Jensen, Nucl. Phys. A 940 (2015) 119 – β to broad resonance
- K.R. et al., Phys. Lett. B732 (2014) 305 – ^{11}Be