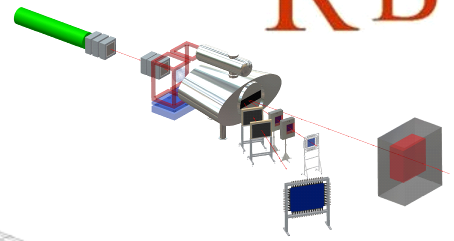
Spectroscopic factors for halo states from knockout reactions and Coulomb breakup



Thomas Aumann

24th April 2012

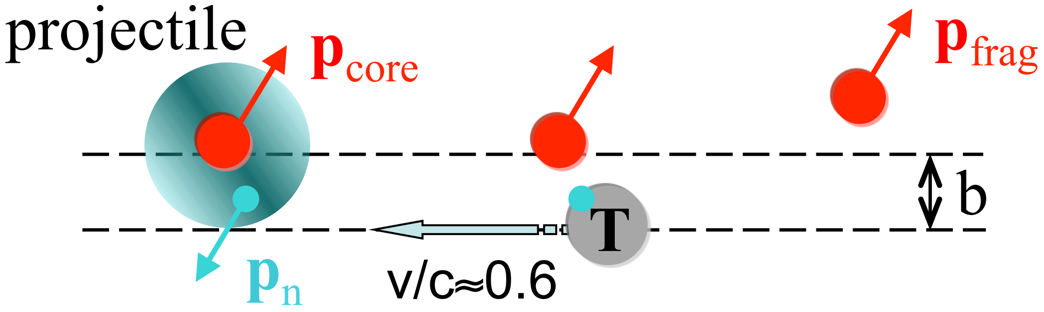
The Extreme Matter Physics of Nuclei:

From Universal Properties to Neutron-Rich Extremes

EMMI workshop April 2012 (GSI)

- Knockout reactions with radioactive beams
- Comparison with Coulomb breakup and sensitivity

One-Nucleon Knockout: a Spectroscopic Tool



Sudden process

Reaction: $\Delta t \approx 10^{-22}$ s

Internal motion: $\approx 10^{-21}$ s

$\Rightarrow$ **$P_{frag} = -P_n$**

$\Rightarrow$ **probing the valence nucleon wave function (at the surface: $b_c > r_c$)**

Example:

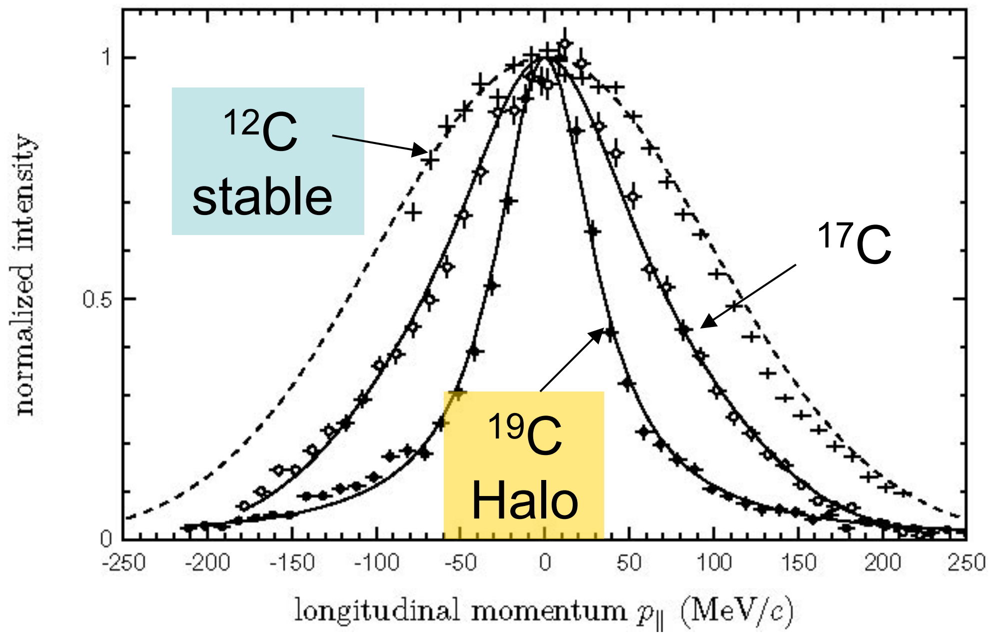
Carbon isotopes

$^{A}C + C \rightarrow {}^{A-1}C + x$

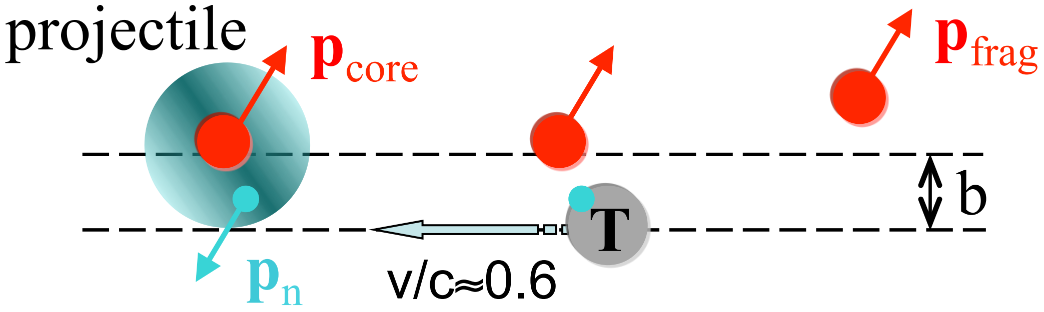
$E \approx 900$ MeV/u

FRS@GSI

T. Baumann et al.



One-Nucleon Knockout: a Spectroscopic Tool



Sudden process

Reaction: $\Delta t \approx 10^{-22}$ s

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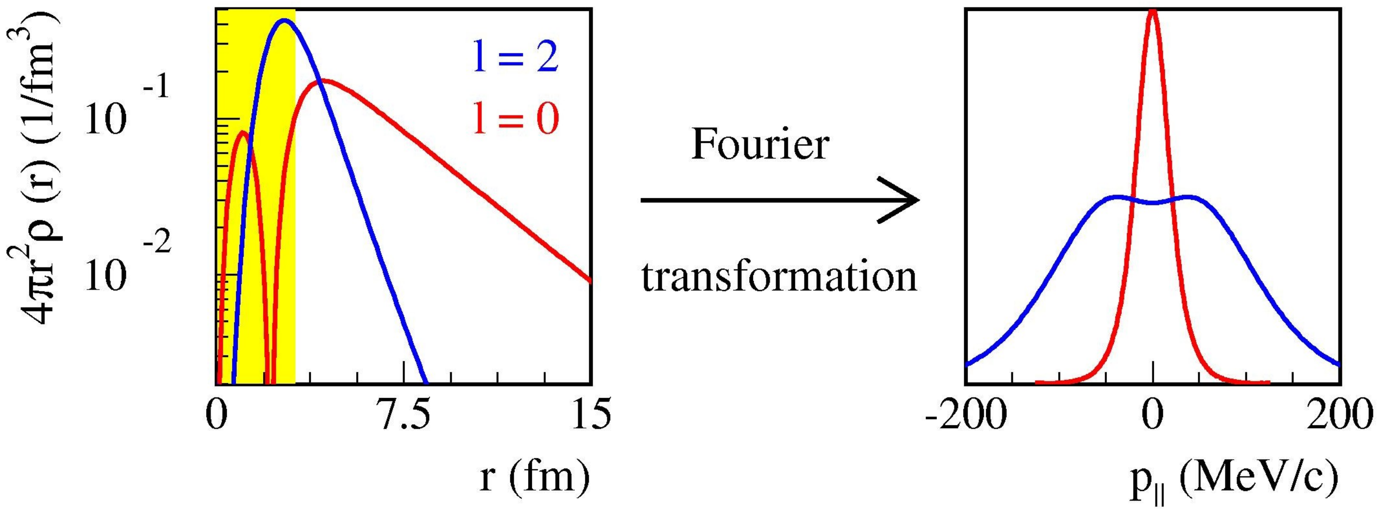
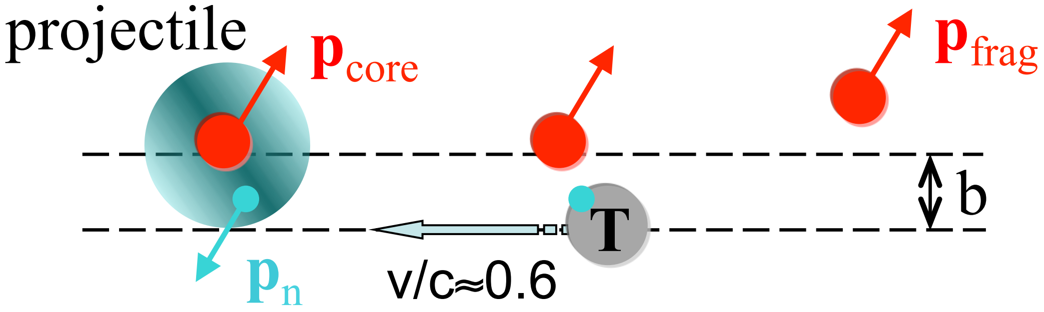
⇒ **probing the valence nucleon wave function (at the surface: $b_c > r_c$)**



Extended Wavefunction

Narrow Momentum Distribution

One-Nucleon Knockout: a Spectroscopic Tool



Sudden process

Reaction: $\Delta t \approx 10^{-22}$ s

Internal motion: $\approx 10^{-21}$ s

⇒ $P_{frag} = -P_n$

⇒ probing the valence nucleon wave function (at the surface: $b_c > r_c$)

Measurement	Extracted Information
Momentum distribution	⇒ l-value of removed nucleon
γ-ray coincidence	⇒ identification of core-state
invariant mass (unbound states)	
Cross section	⇒ spectroscopic factor

$$\sigma_{1n}(J^\pi) = S(J^\pi) \times \sigma_{sp}(l, S_n)$$

Eikonal calculation

Single-particle cross sections

$$\sigma_{sp}(J^\pi) = \sigma_{sp}^{knockout} + \sigma_{sp}^{diffraction}$$

Eikonal approximation:

$$\sigma_{sp}^{knockout}(J^\pi) = \int d^2b \int d^3r \; |\Phi_{l,S_n}(\mathbf{r})|^2 \; S_c^2(\mathbf{b_c}) \; (1 - S_n^2(\mathbf{b_n}))$$

core survival

'shadowing'

reaction

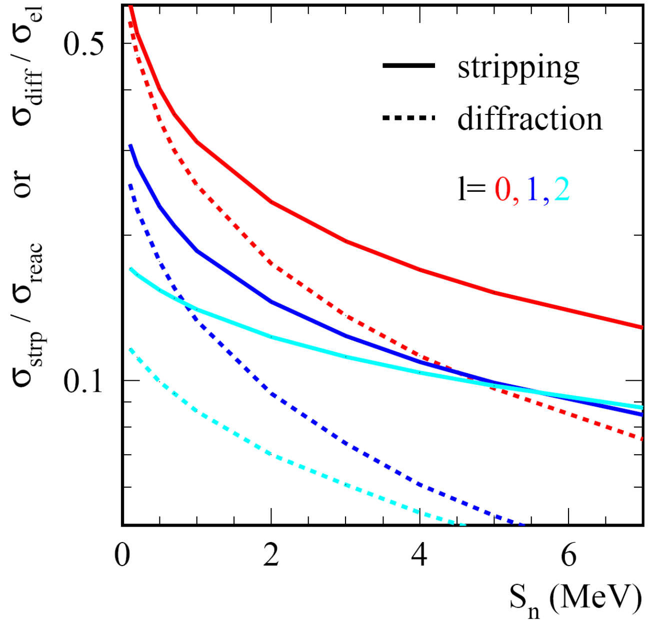
n + target

– $\Phi_{l,S_n}(\mathbf{r})$ is calculated for a Woods-Saxon Potential

– S_c, S_n are calculated using target and core density distributions + free NN cross sections + energy dep. ratio of imaginary to real part

→ no free parameters

One-neutron removal reaction (nuclear breakup)



Reaction mechanisms:

- knockout (stripping)
- inelastic scattering (diffraction)

cross section dominated by knockout for

- high beam energies
- non-halo states

$$p_{stripping} = < S_c^2(\mathbf{b_c})[1 - S_n^2(\mathbf{b_n})] >$$

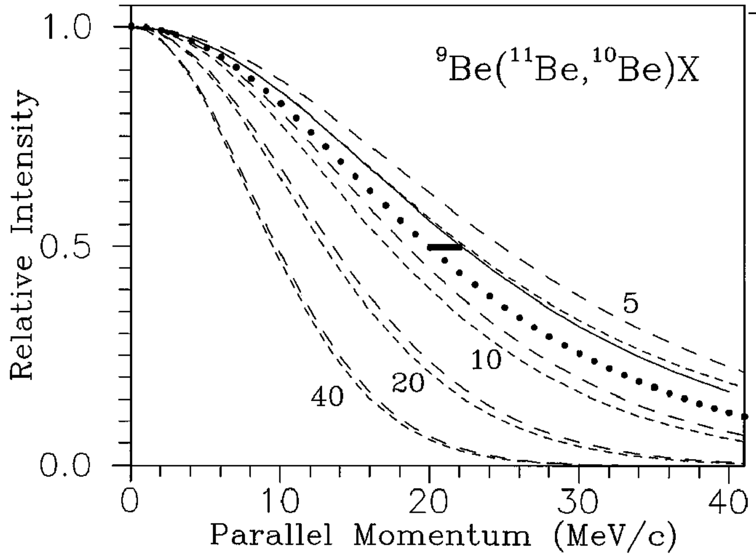
$$p_{inelastic} = < [1 - S_c(\mathbf{b_c})S_n(\mathbf{b_n})]^2 > - < 1 - S_c(\mathbf{b_c})S_n(\mathbf{b_n}) >^2$$

<u>no-recoil limit:</u> $A_c >> 1, \mathbf{b_c} = \mathbf{b}$

$$p_{diffraction} = S_c^2 < [1 - S_n(\mathbf{b_n})]^2 > - S_c^2 < 1 - S_n(\mathbf{b_n}) >^2$$

elastic scattering of neutron — elastic scattering of projectile

Momentum distributions and reaction mechanism



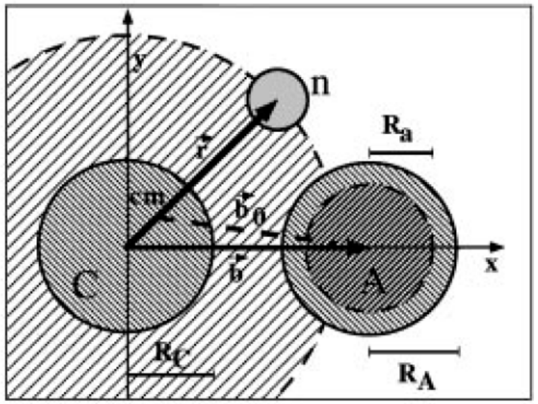
VOLUME 77, NUMBER 6 PHYSICAL REVIEW LETTERS 5 AUGUST 1996

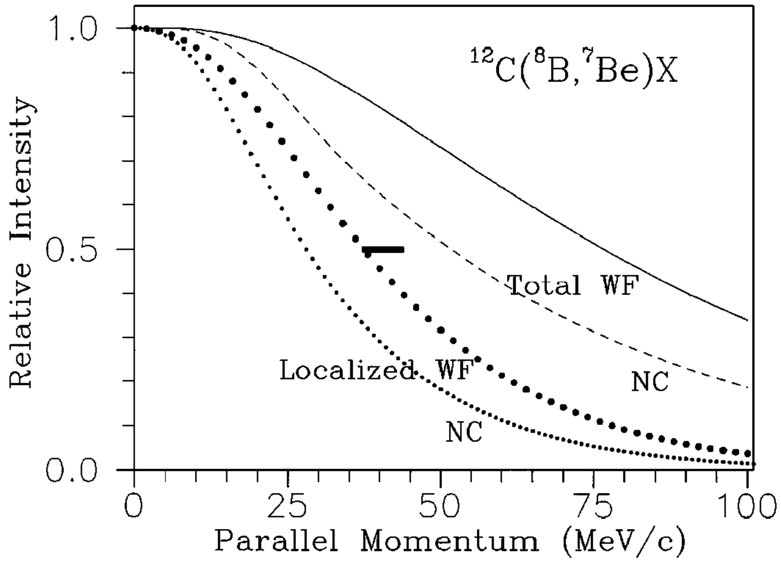
Momentum Content of Single-Nucleon Halos

P. G. Hansen

National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824-1321

(Received 12 January 1996)





reaction samples only the surface of the nucleus

→ momentum distributions are more narrow than the full Fourier transform

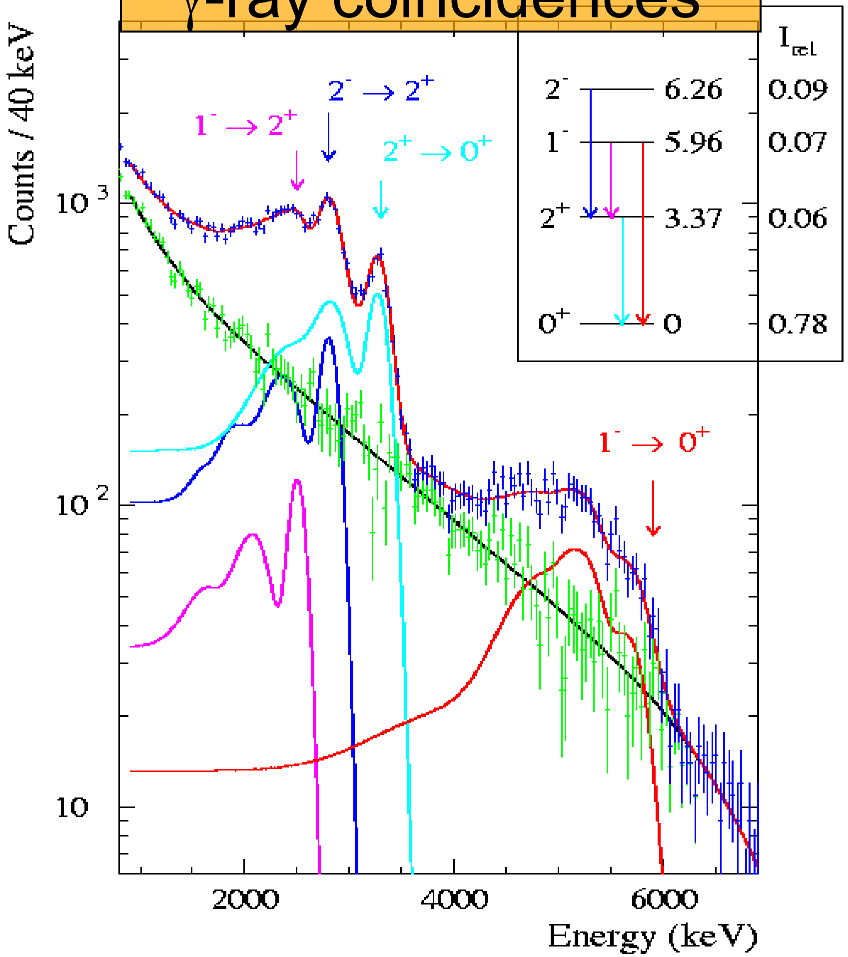
effect less pronounced for well developed halos

Neutron removal from individual single-particle states: $^{11}Be \rightarrow {}^{10}Be(I^{\pi}) + \gamma + X$

Wave function: e.g. $|^{11}Be\rangle = \alpha|^{10}Be(0^+)\otimes 2s_{1/2}\rangle + \beta|^{10}Be(2^+)\otimes 1d_{5/2}\rangle + \dots$

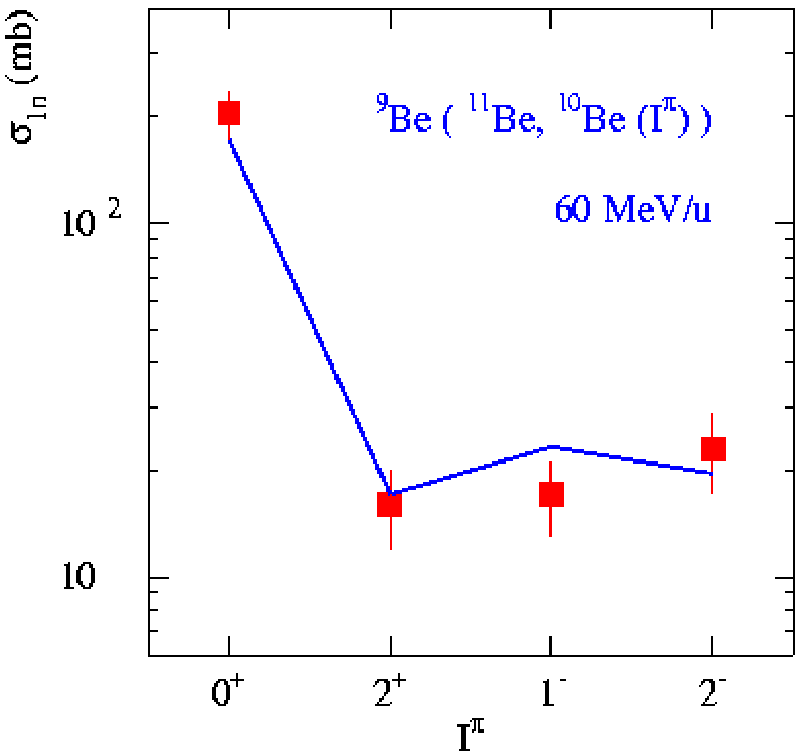
60 MeV/u $^{11}Be + Be \rightarrow {}^{10}Be + \gamma + X$

γ-ray coincidences



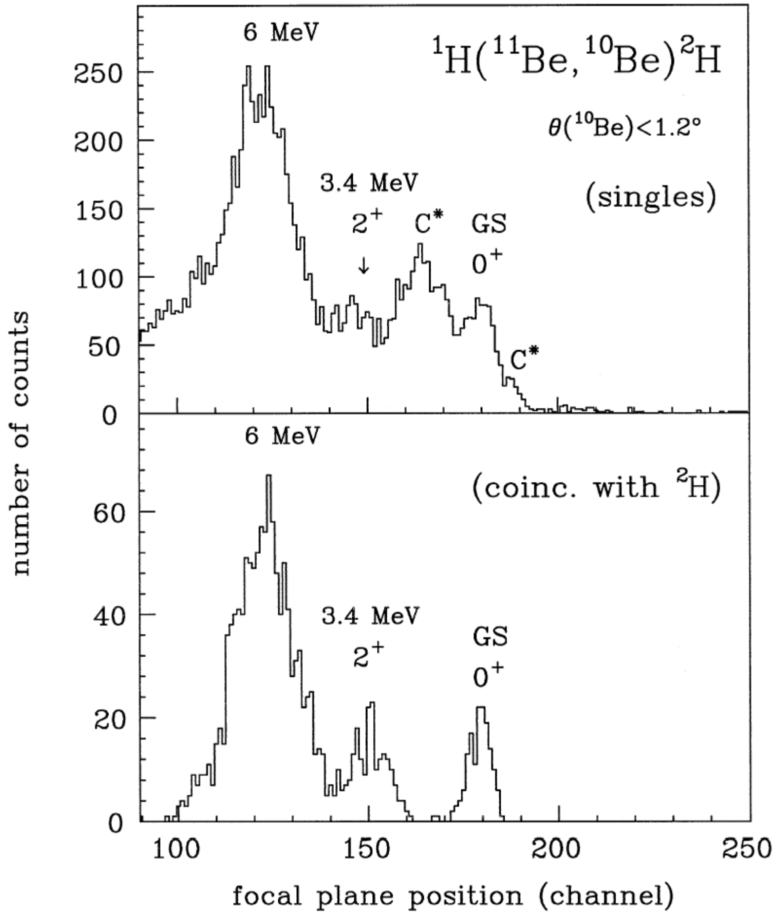
Data: S800@MSU, T.Aumann *et al.*, PRL 84 (2000) 35

Partial cross sections



Spectroscopic factors
$S(0^+) \approx 0.8$
$S(2^+) \approx 0.2$

Comparison to transfer reactions



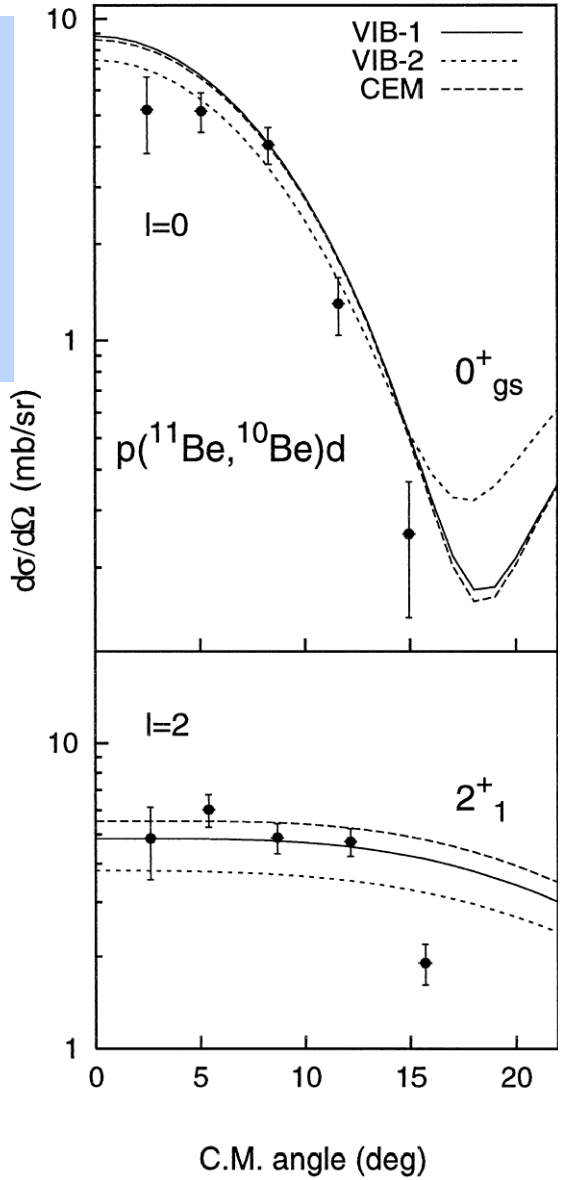
Transfer reaction in inverse kinematics:

GANIL, 35 MeV/u ^{11}Be

S. Fortier et al.,
PLB 461 (1999) 22

deduced spectroscopic factors in agreement with knockout reaction

E_x (MeV)	J^π	SE-1 S_{exp}	VIB-1 S_{exp}	VIB-1 S_{th}	SE-2 S_{exp}	VIB-2 S_{exp}	VIB-2 S_{th}
0	0^+	0.66	0.67	0.84	0.79	0.79	0.84
3.368	2^+	0.28	0.17	0.16	0.38	0.22	0.16

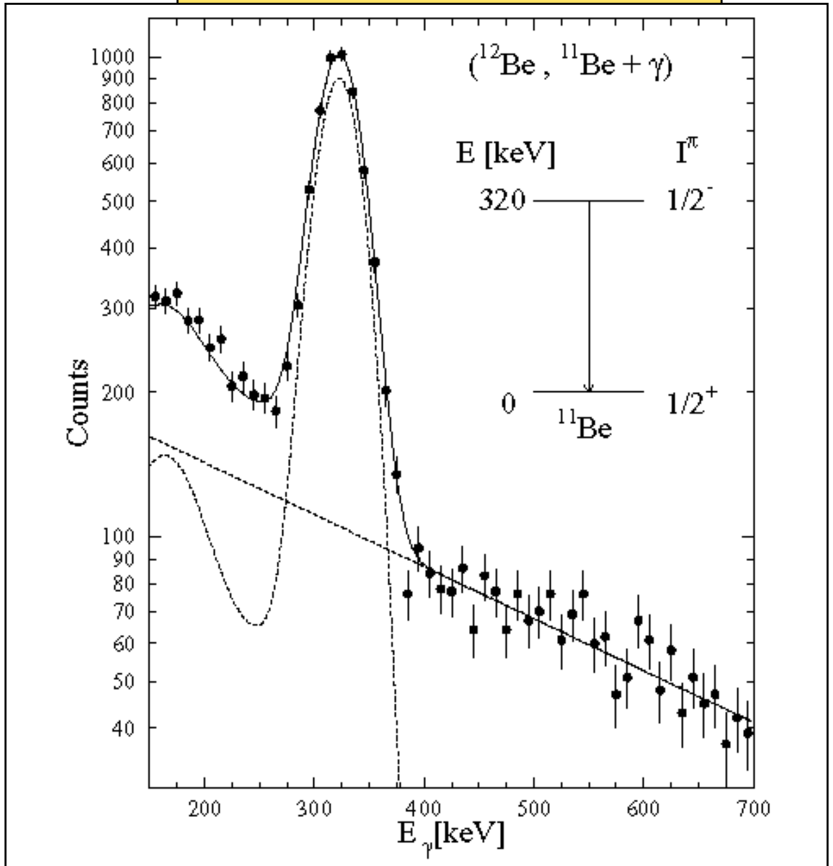


^{12}Be: Breakdown of the N=8 Shell Closure

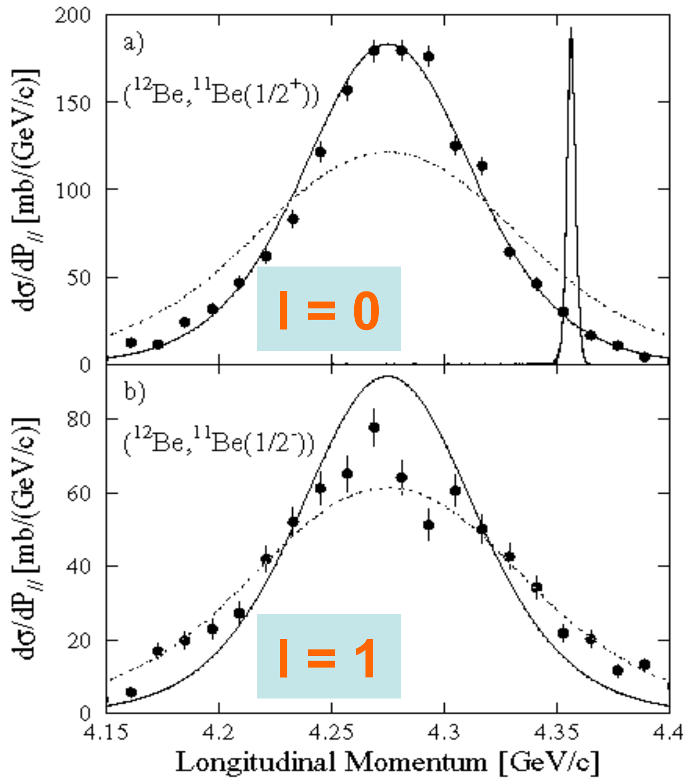
One-neutron removal reaction:

^{12}Be (@78 Mev/u) + ^{9}Be $\rightarrow$ ^{11}Be(I^{π}) + γ + X

γ-ray coincidences



Momentum distributions

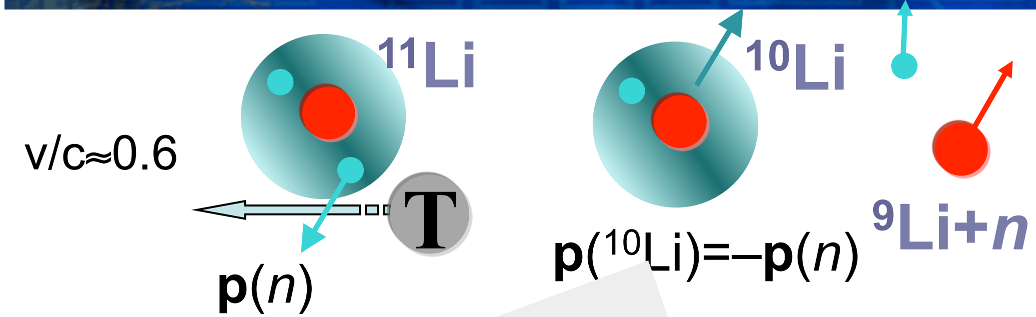


⇒ Mixed configurations

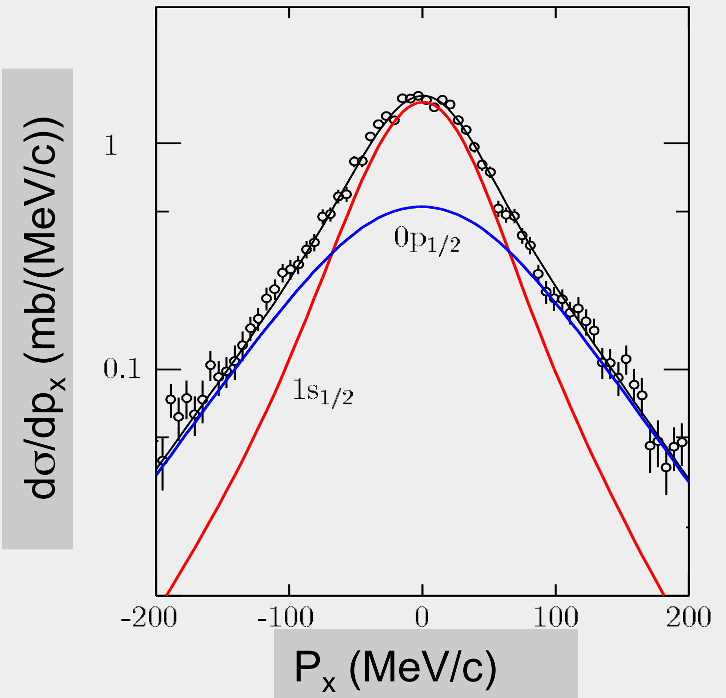
$(\nu s_{1/2})^2 \,/\, (\nu p_{1/2})^2 \approx 1$

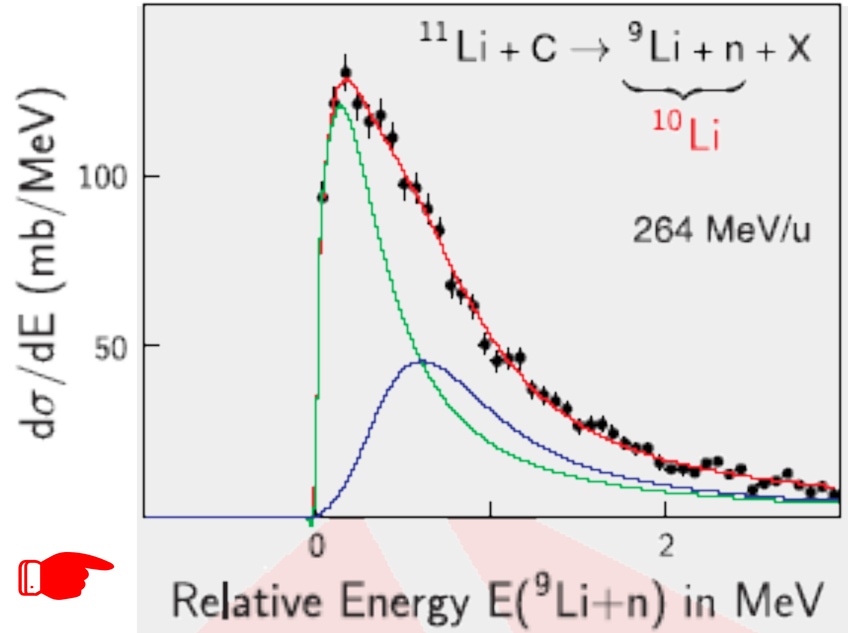
Data: S800@MSU, A. Navin *et al.*, PRL 85 (2000) 266

The halo of ^{11}Li: *s* and *p* waves

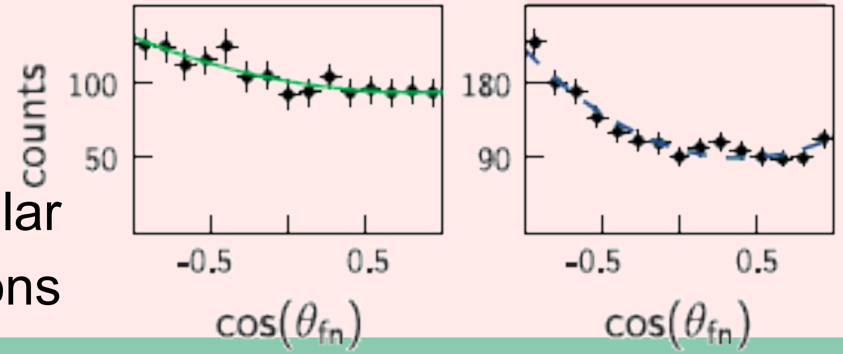


Momentum distribution ^{10}Li





Angular correlations



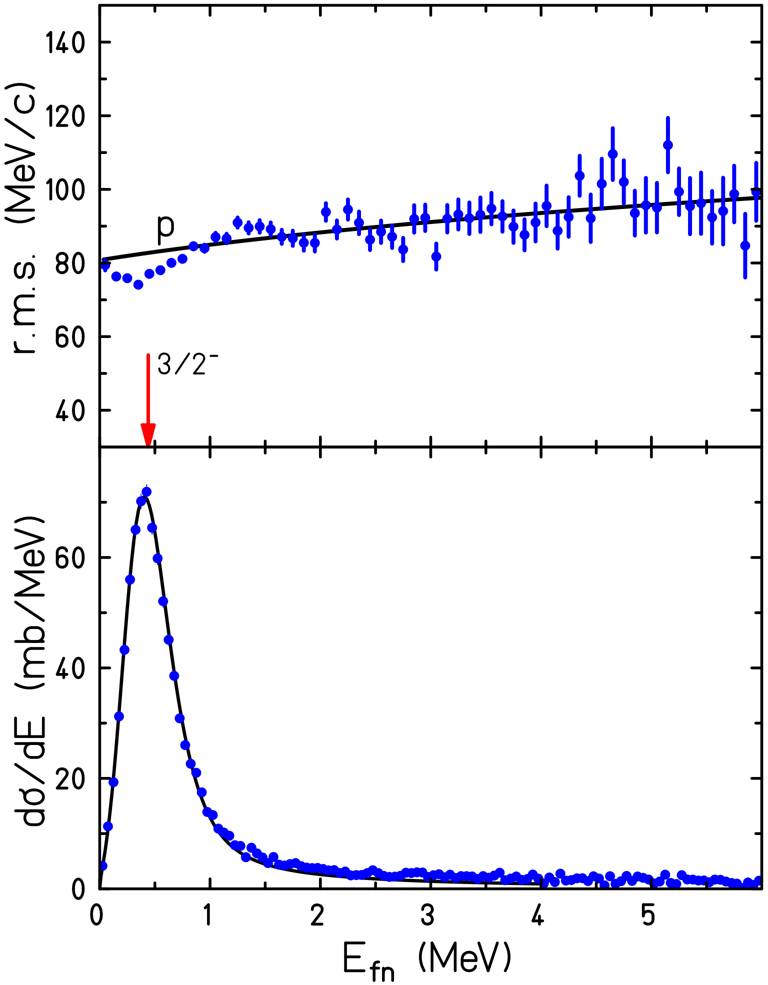
⇒ **Strong *s*-wave admixture**

$(s_{1/2})^2 / (p_{1/2})^2 \approx 1$

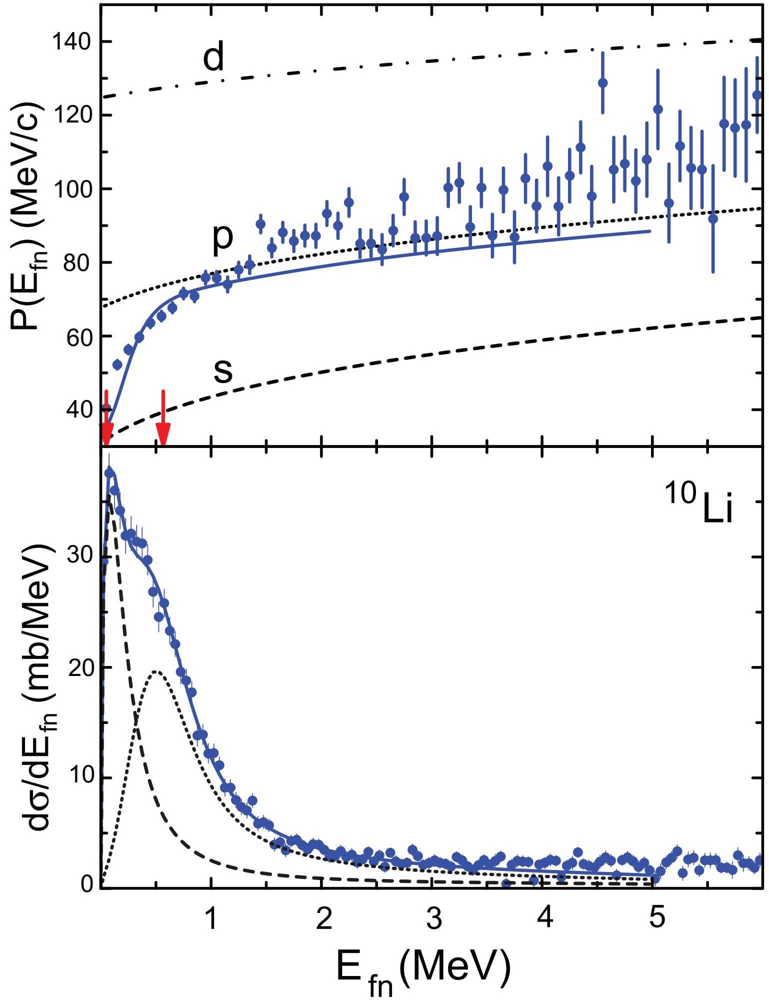
Data: LAND-FRS@GSI, H. Simon et al., Phys. Rev. Lett. 83 (99) 496

Momentum profile (rms width) as a function of relative energy in the unbound subsystem populated in 1n knockout

8He (p,pn) 7He -> 6He + n



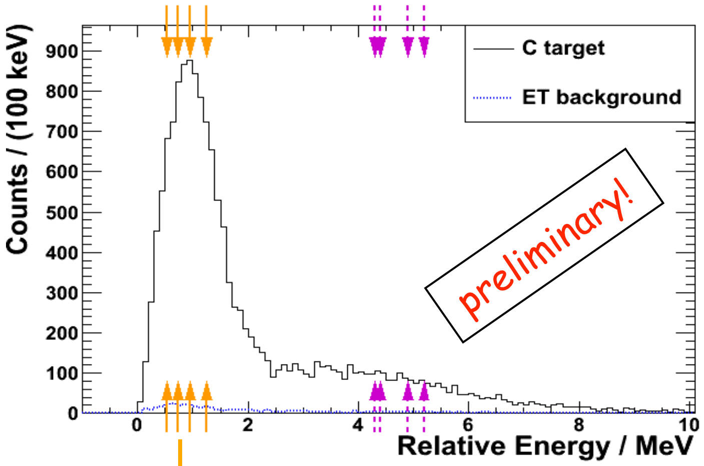
11Li (p,pn) 10Li -> 9Li + n

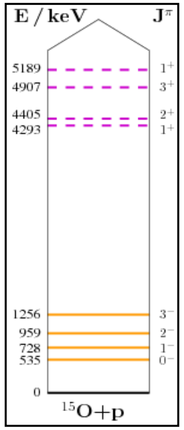


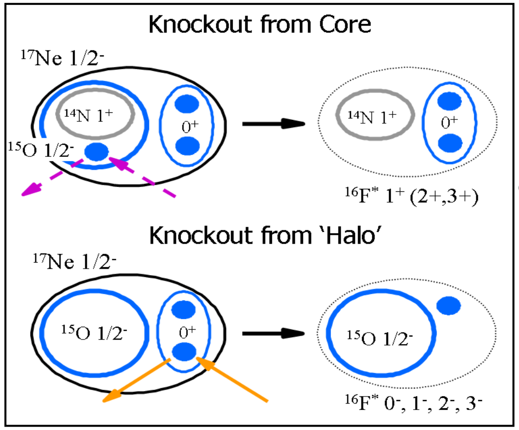
Yu. Aksyutina et al. (2012), LAND/GSI data, to be published

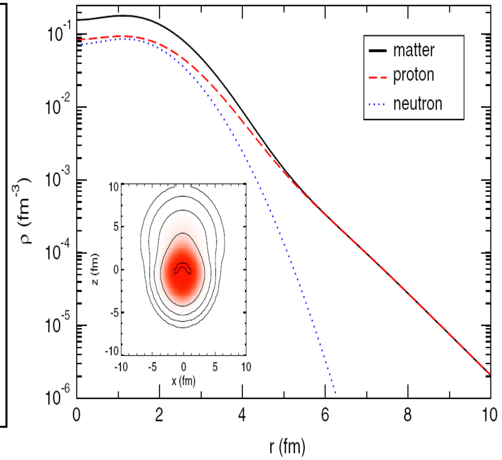
Selective one-proton knockout from core- and 'Halo'- states in ^{17}Ne

^{16}F (=^{15}O+p) relative energy

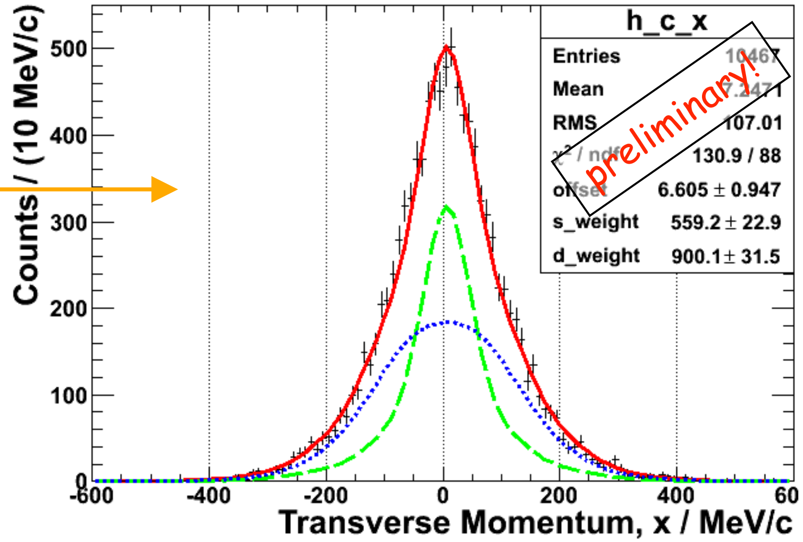








Exclusive selection of knockout from 'halo'-states for the first time possible!



s-wave content of ~40%
moderate halo character

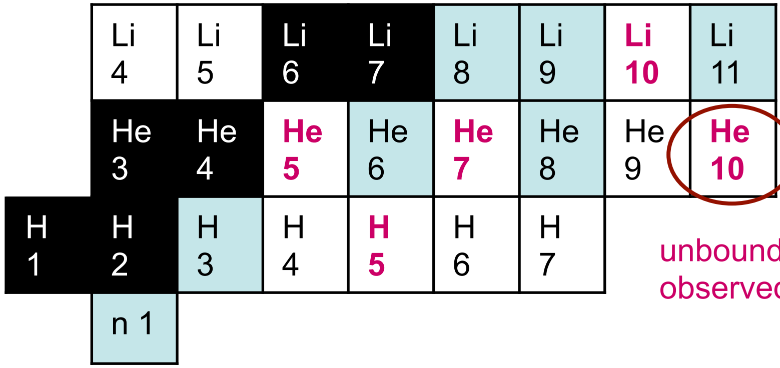
Good agreement with charge-radius measurement and FMD prediction of Geithner and Neff et al. *PRL 101 (2008) 252502.*
and from 3b-model of Grigorenko, *PRC 71 (2005) 051604(R).*

Felix Wamers, PhD thesis,

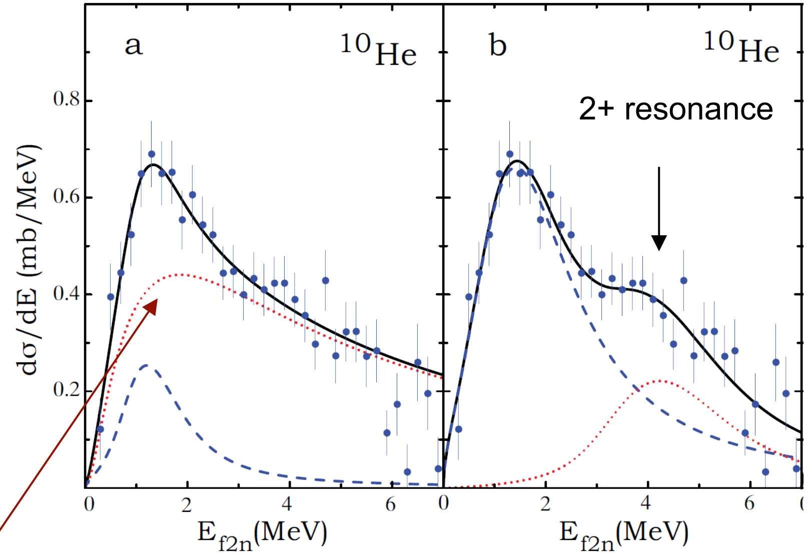
TU Darmstadt

F. Wamers et al. (2012), LAND/R3B data, to be published

Beyond the dripline: Ground and first excited state of ^{10}He
- three-body correlations in the decay of unbound nuclei -



unbound nuclei observed at R3B



Unbound nuclear systems

problem of overlapping resonances

ambiguity: resonances or correlated background?

solution demonstrated for ^{10}He:

observation of characteristic 3-body correlations in the decay

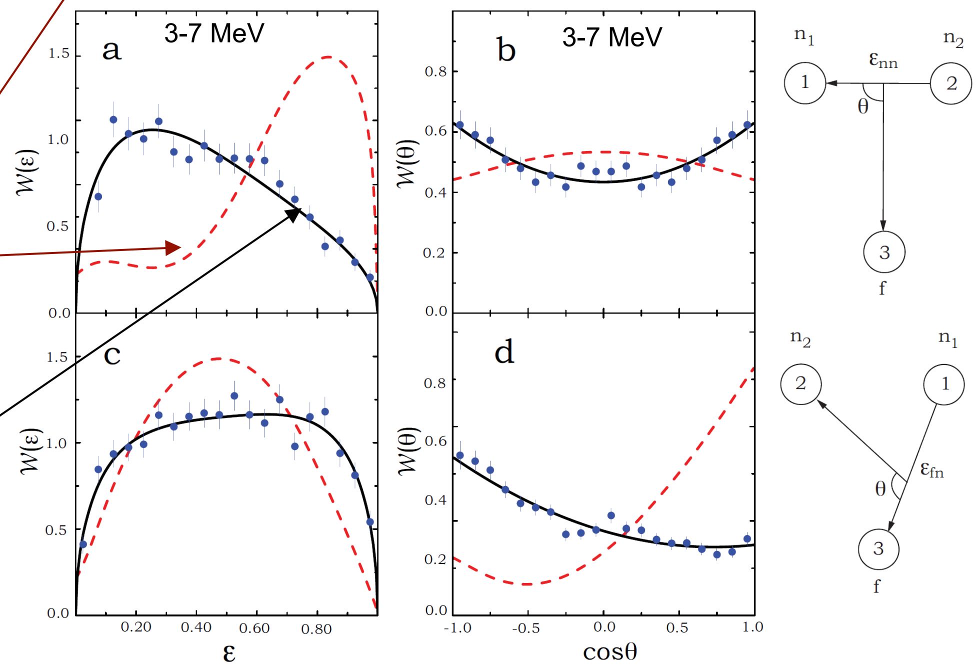
identification of ^{10}He resonances produced in ^{11}Li(p,2p) reactions:

0^+ ground state

2^+ excited state

correlated background
(initial-state correlations,
^{11}Li wave function)

2+ resonance



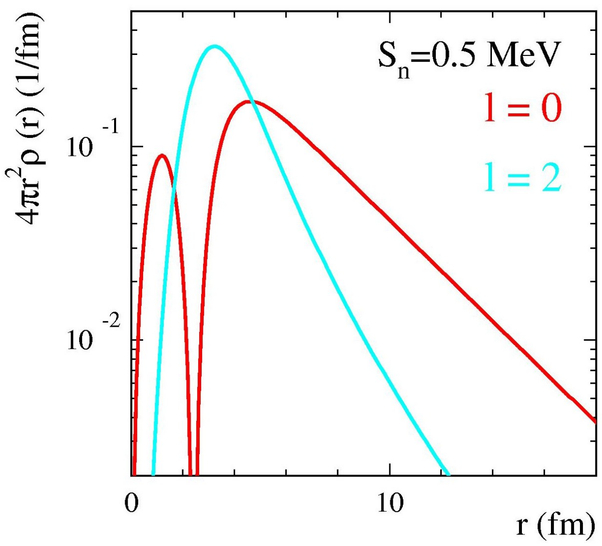
H.T. Johansson, Yu. Aksyutina et al., NPA 842 (2010) 15.

Low-Lying E1 Strength as Spectroscopic Tool

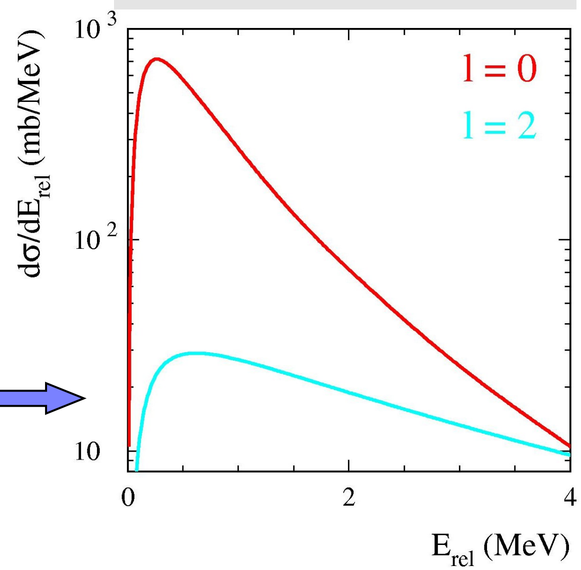
Wave function: e.g. $|^{11}\mathrm{Be}\rangle = \alpha|^{10}\mathrm{Be}(0^+)\otimes 2s_{1/2}\rangle + \beta|^{10}\mathrm{Be}(2^+)\otimes 1d_{5/2}\rangle + \ldots$

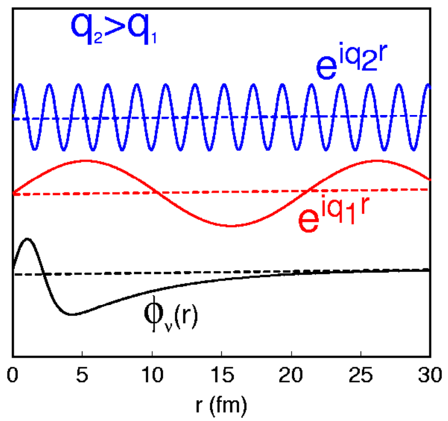
$$d\sigma(I_c^\pi)/dE_{rel} = \frac{16\pi^3}{9\hbar c} N_{E1}(E^*)\; S(I_c^\pi, nlj) \sum_m \left|\langle q \,|\, \frac{Ze}{A} r Y^l_m \,|\, \Phi_{nlj} \rangle\right|^2$$

Density distribution



Differential cross section





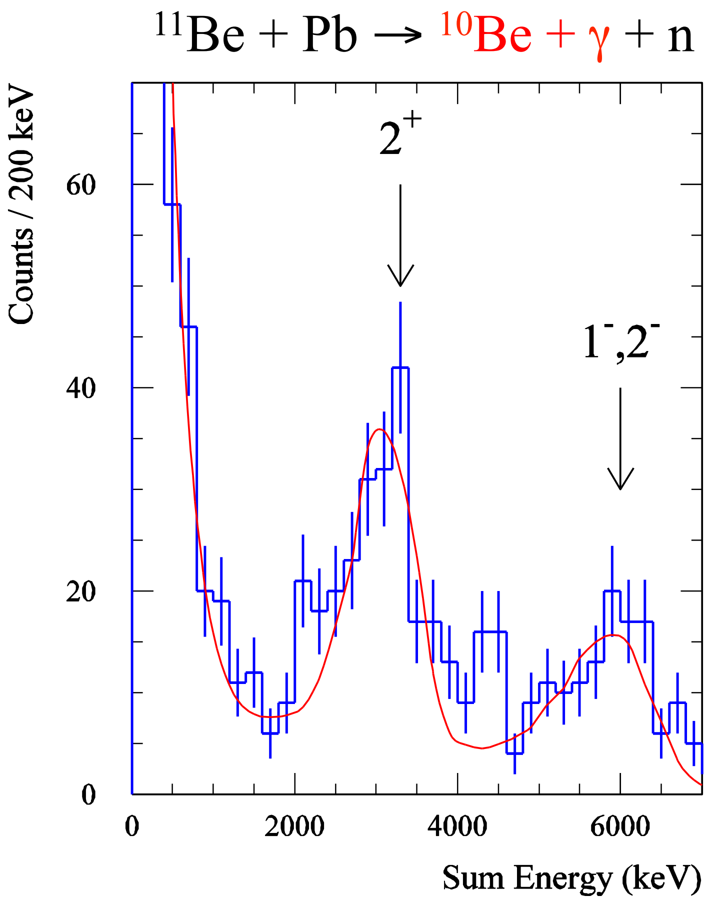
Shape of differential cross section ⇒ angular momentum *l*

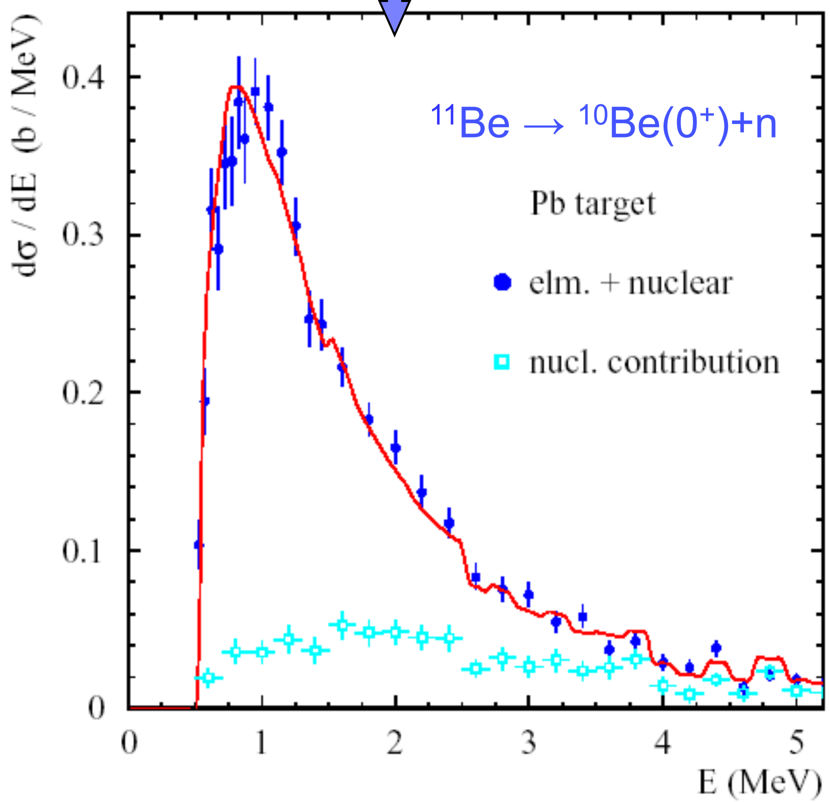
γ-ray coincidence ⇒ identification of core state

Cross section ⇒ spectroscopic factor

Coulomb Breakup of ^{11}Be at 500 MeV/nucleon: The Classical One-Neutron Halo

$$|^{11}\mathrm{Be}\rangle = \sqrt{S(2^+)}\,|^{10}\mathrm{Be}(2^+)\otimes 1d_{5/2}\rangle + \underbrace{\sqrt{S(0^+)}\,|^{10}\mathrm{Be}(0^+)\otimes 2s_{1/2}\rangle}_{} + \ldots$$





ph states at 6 MeV (inner shell p neutrons lifted into continuum)

R. Palit et al., PRC 68 (2003) 034218

Coulomb Breakup of ^{11}Be: The Classical One-Neutron Halo

$$|^{11}\mathrm{Be}\rangle = \sqrt{S(2^+)}\,|^{10}\mathrm{Be}(2^+)\otimes 1d_{5/2}\rangle + \underbrace{\sqrt{S(0^+)}\,|^{10}\mathrm{Be}(0^+)\otimes 2s_{1/2}\rangle}_{} + \ldots$$

<u>Spectroscopic factor</u>

Analysis in the effective range approach:

$S(0^+)=0.70(5)$

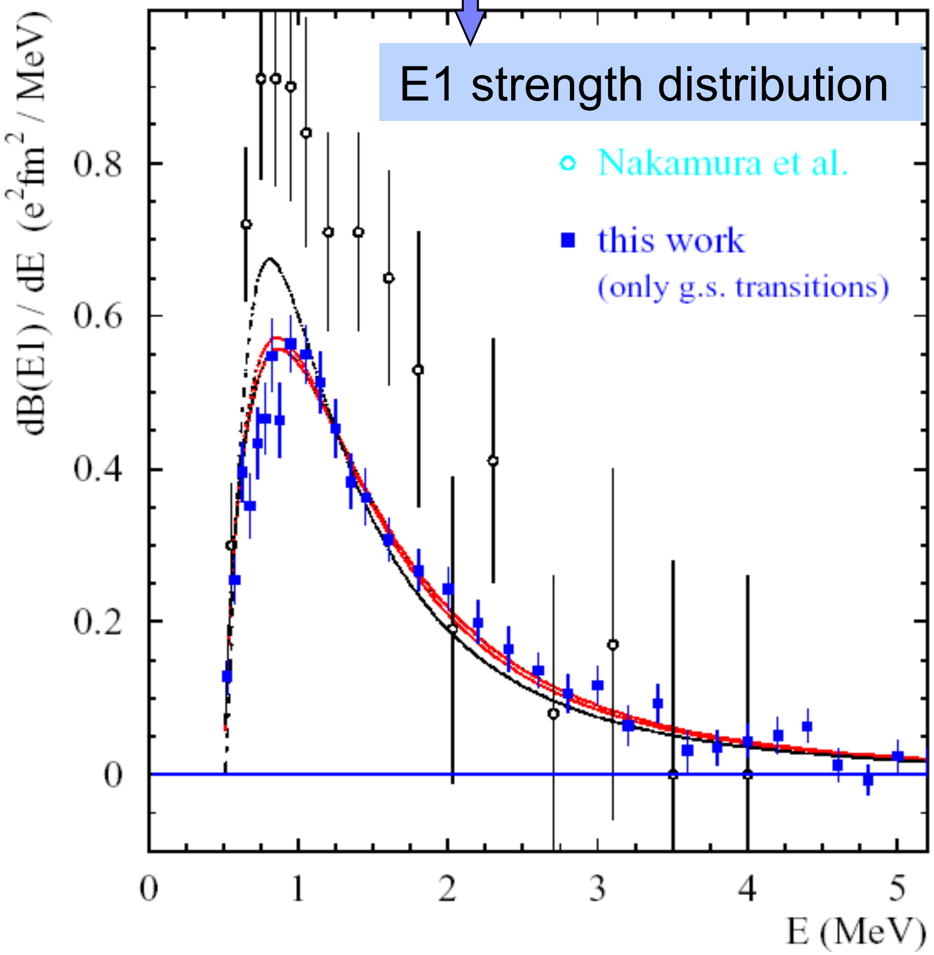
S. Typel, G. Baur, PRL **93** (2004) 142502

Distorted wave analysis:
S = 0.61(5) with diff. opt. pot.
(S = 0.54 for plane waves)

S = 0.74(6) for WS changed from r0/a =1.25/0.7 to 1.15/0.5

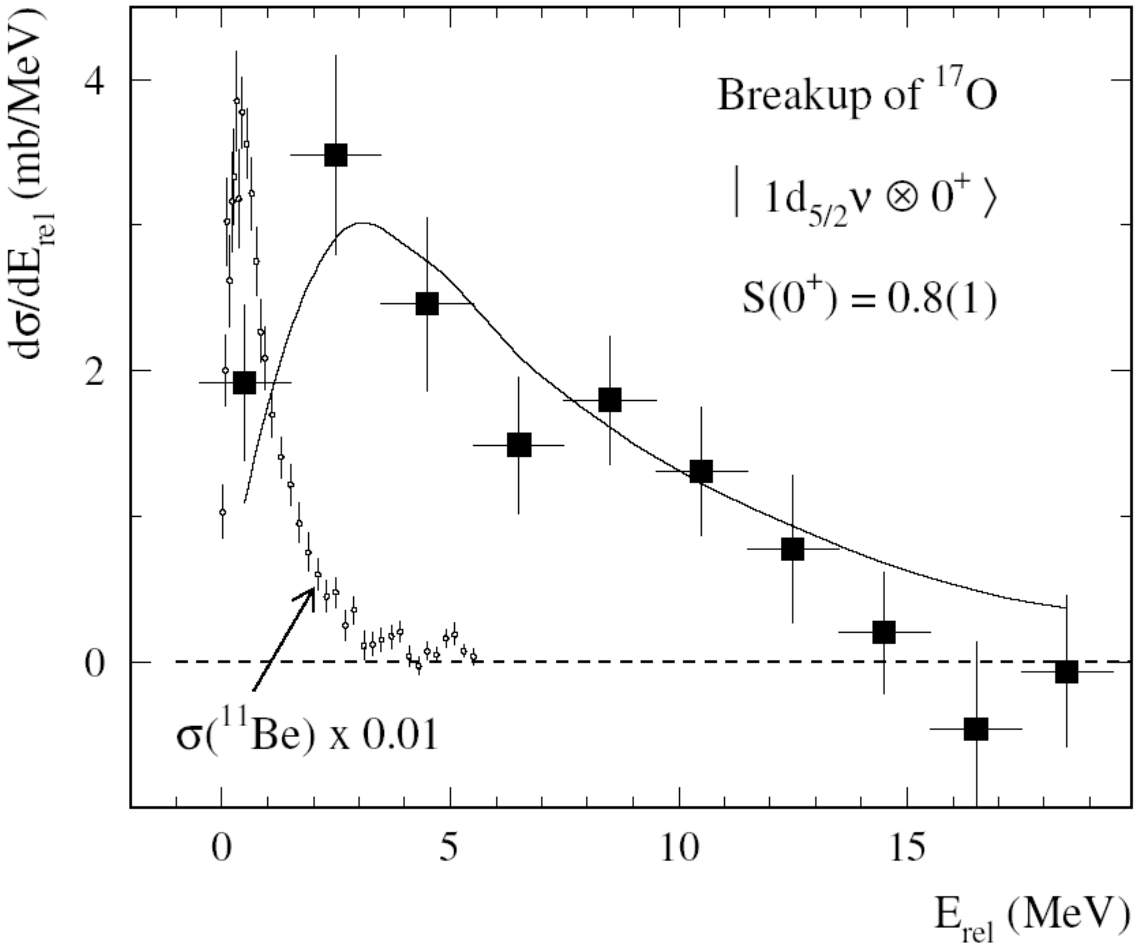
Alex Brown: 0.74

R. Palit et al., PRC 68 (2003) 034218



Sensitivity of Coulomb breakup

Comparison of the one-neutron halo ^{11}Be with the well bound ^{17}O d neutron



Coulomb breakup is very sensitive to extended neutron-density distributions (halo)

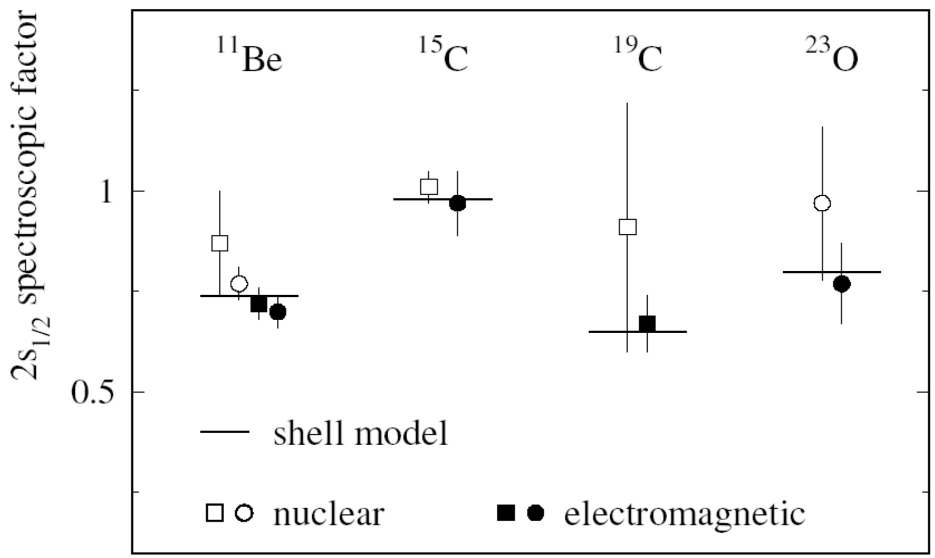
→ applicability as a spectroscopic tool mainly for weakly bound nuclei (large cross sections)

R. Palit et al.,

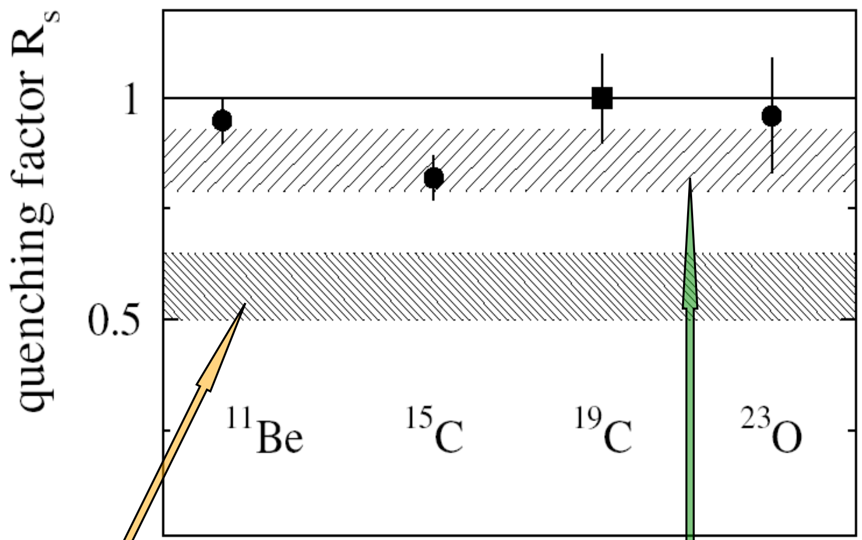
NPA 731 (2004) 235

Single-particle spectroscopic factors for halo nuclei derived from nuclear and electromagnetic knockout reactions

Spectroscopic factors for $2s_{1/2}$ halo states derived from nuclear and Coulomb breakup in comparison to the shell model



Ratio of experimental occupancies to shell-model values



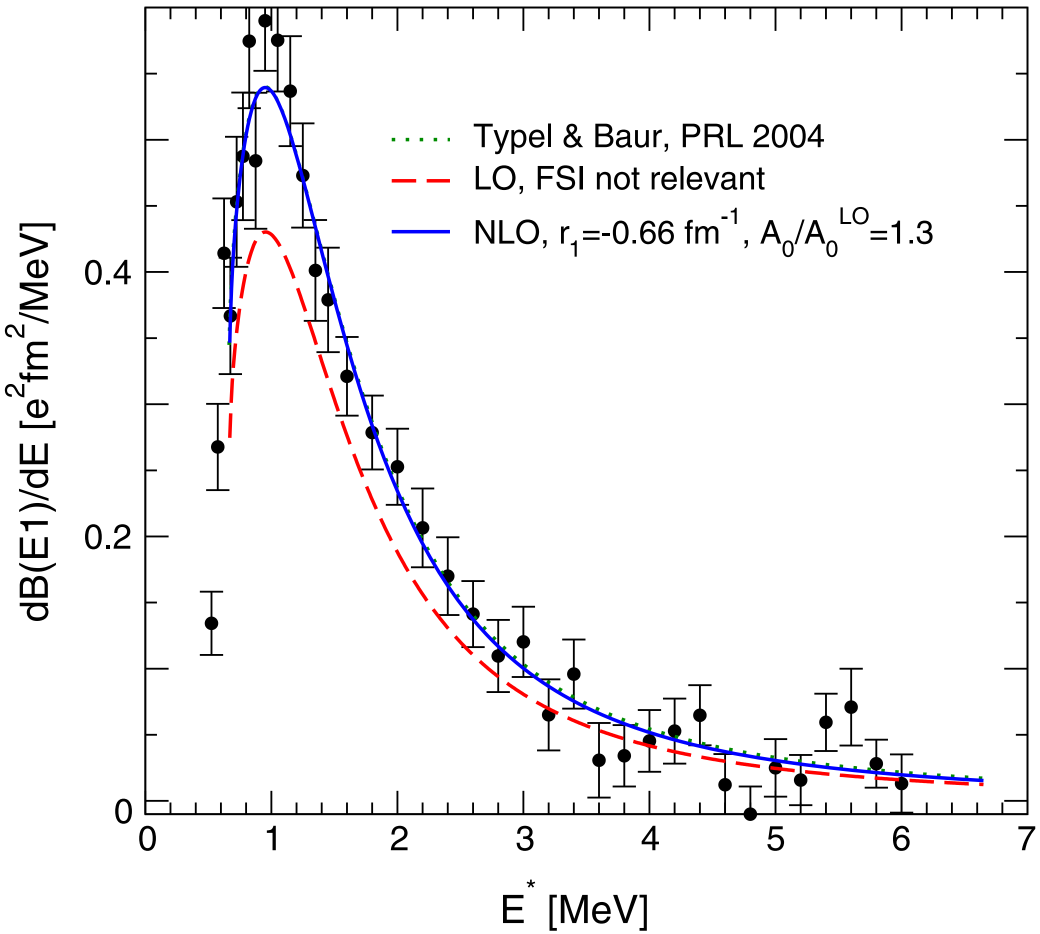
Typical reduction observed for stable nuclei (deduced from electron-induced knockout reactions)

effect of short- and long-range correlations ?

Halo states

(pure single-particle states)

Electric properties of the Beryllium-11 system in Halo EFT



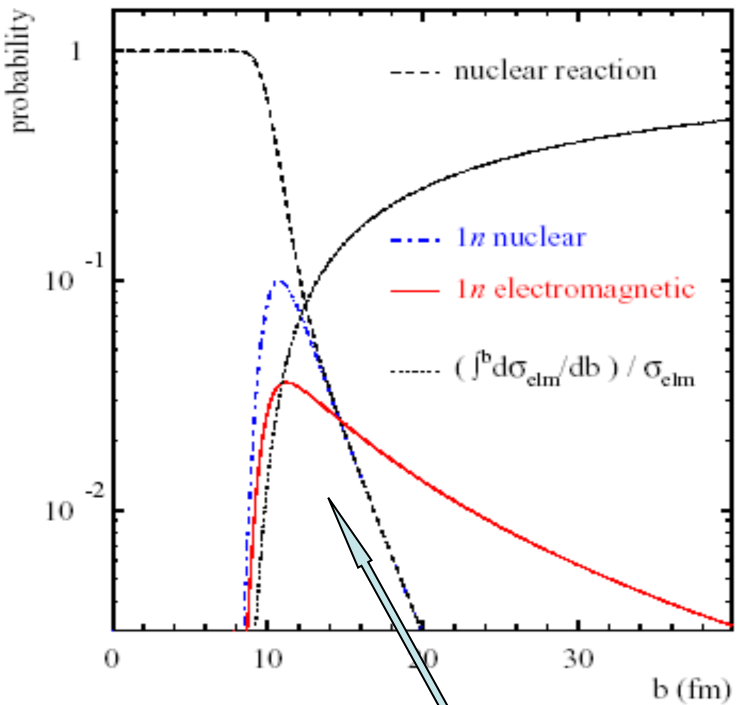
Differential B(E1) strength for Coulomb dissociation of Beryllium-11 into a neutron and a 10Be nucleus, plotted versus the excess energy of the detected neutron E∗, in MeV. The data are from Ref. [5]. The theory curves have been folded with detector resolution. The red dashed line is the leading-order Halo EFT prediction, which does not include any final-state interactions. Final-state interactions, with the effective range taking on a value fixed from the bound-to-bound E1 transition strength, are included in the NLO result, which is shown by the solid blue line. The result of Ref. [30] is the green dotted line, which essentially matches the solid blue line

H.-W. Hammer and D.R. Phillips, Nucl. Phys. A 865 (2011) 17

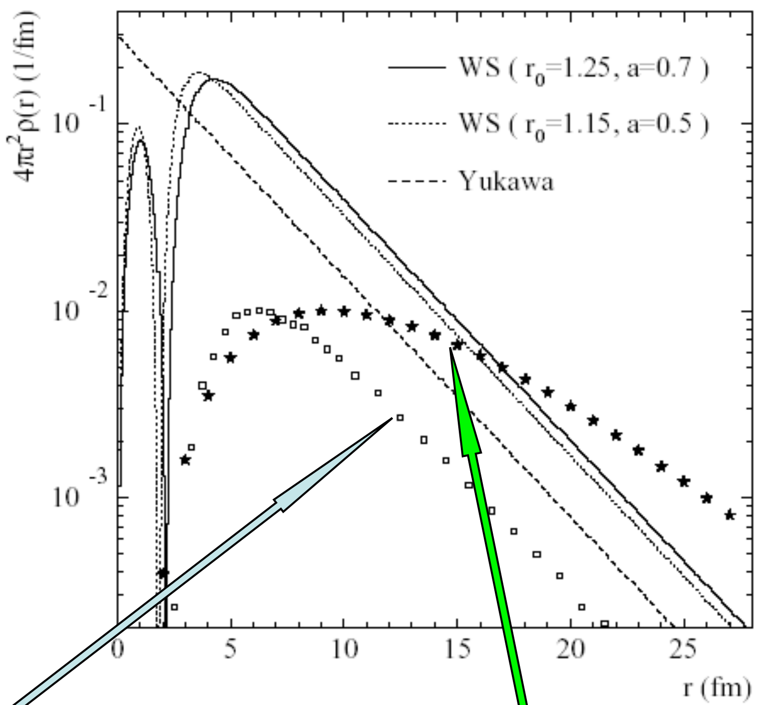
GSI/LAND data: R. Palit et al., PRC 68 (2003) 034218

Sensitivity of Coulomb and nuclear breakup

Reaction probabilities



Halo-Neutron Densities



Nuclear breakup

Coulomb breakup

Overlap with continuum wave function

Sensitivity to the tail of the wave function only

Alternative approach: quasi-free scattering: (p,2p), (p,pn) etc. at LAND and R3B

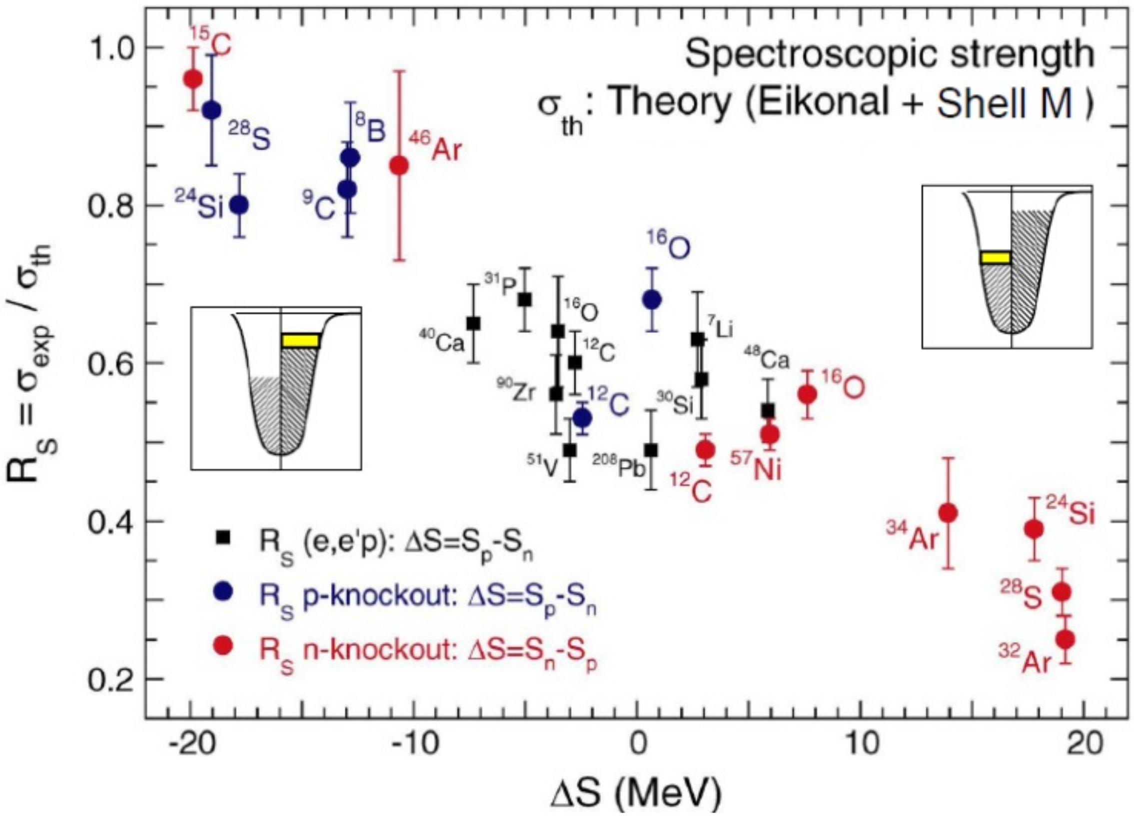
(or (e,e'p) at the e-A collider at FAIR)

See talk of Roy Lemmon

Single-particle cross sections
Quenching for neutron-proton asymmetric nuclei

weakly bound nucleons

strongly bound nucleons

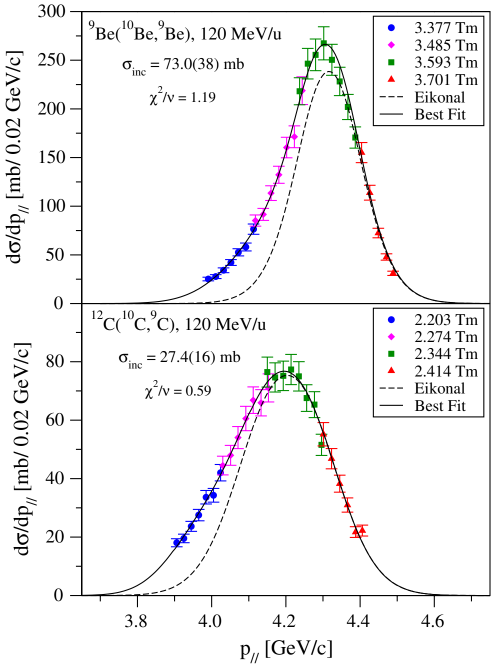


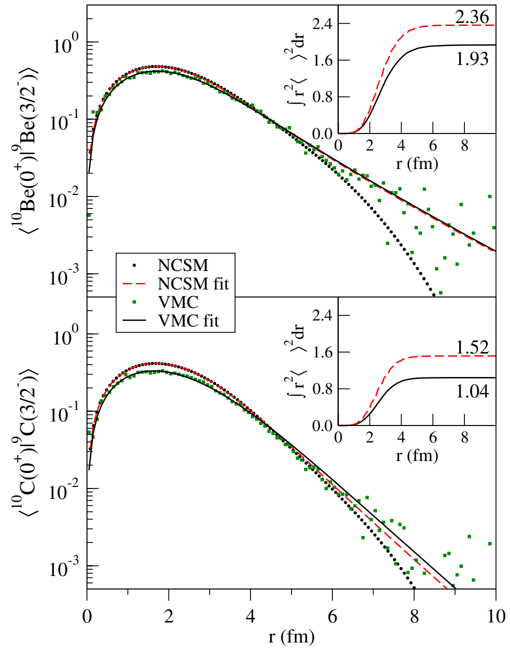
?

Origin unclear

?

Figure from Alexandra Gade, Phys. Rev. C 77, 044306 (2008)





G. F. Grinyer et al.
PRL 106, 162502 (2011)
MSU data

FIG. 2 (color online). Bound-state VMC and NCSM wave function overlaps and resulting fits that use a Woods-Saxon-plus-spin-orbit potential. (Inset) Integrals of the square overlaps that saturate at the theoretical spectroscopic factor.

TABLE II. Woods-Saxon parameters r, a, and potential depth V_0 for the $\langle^{10}\mathrm{Be}|^{9}\mathrm{Be}+n\rangle$ and $\langle^{10}\mathrm{C}|^{9}\mathrm{C}+n\rangle$ overlap fits. Single-particle cross sections σ_{sp} were derived for projectile beam energies of 120 MeV/u on a ^{9}Be target. Spectroscopic factors S_F from each model are used to derive theoretical cross sections σ_{th} and can be compared to the experimental results σ_{exp}.

$\langle^{10}\mathrm{Be}\|^{9}\mathrm{Be}+n\rangle$	r (fm)	a (fm)	V_0 (MeV)	σ_{sp} (mb)	S_F	σ_{th} (mb)	σ_{exp} (mb)
SM	1.25	0.70	60.4	36.8	2.62	96.6	
NCSM	1.34(2)	0.57(2)	42.9	36.8(7)	2.36	86.9(16)	73(4)
VMC	1.25(3)	0.78(4)	48.0	37.7(7)	1.93	72.8(13)	
$\langle^{10}\mathrm{C}\|^{9}\mathrm{C}+n\rangle$							
SM	1.06	0.70	91.1	24.8	1.93	48.0	
NCSM	1.51(2)	0.79(2)	61.6	28.6(6)	1.52	43.4(9)	23.2(10)
VMC	1.38(4)	1.14(6)	70.9	29.5(6)	1.04	30.8(6)	