Electromagnetic dissociation of halo nuclei

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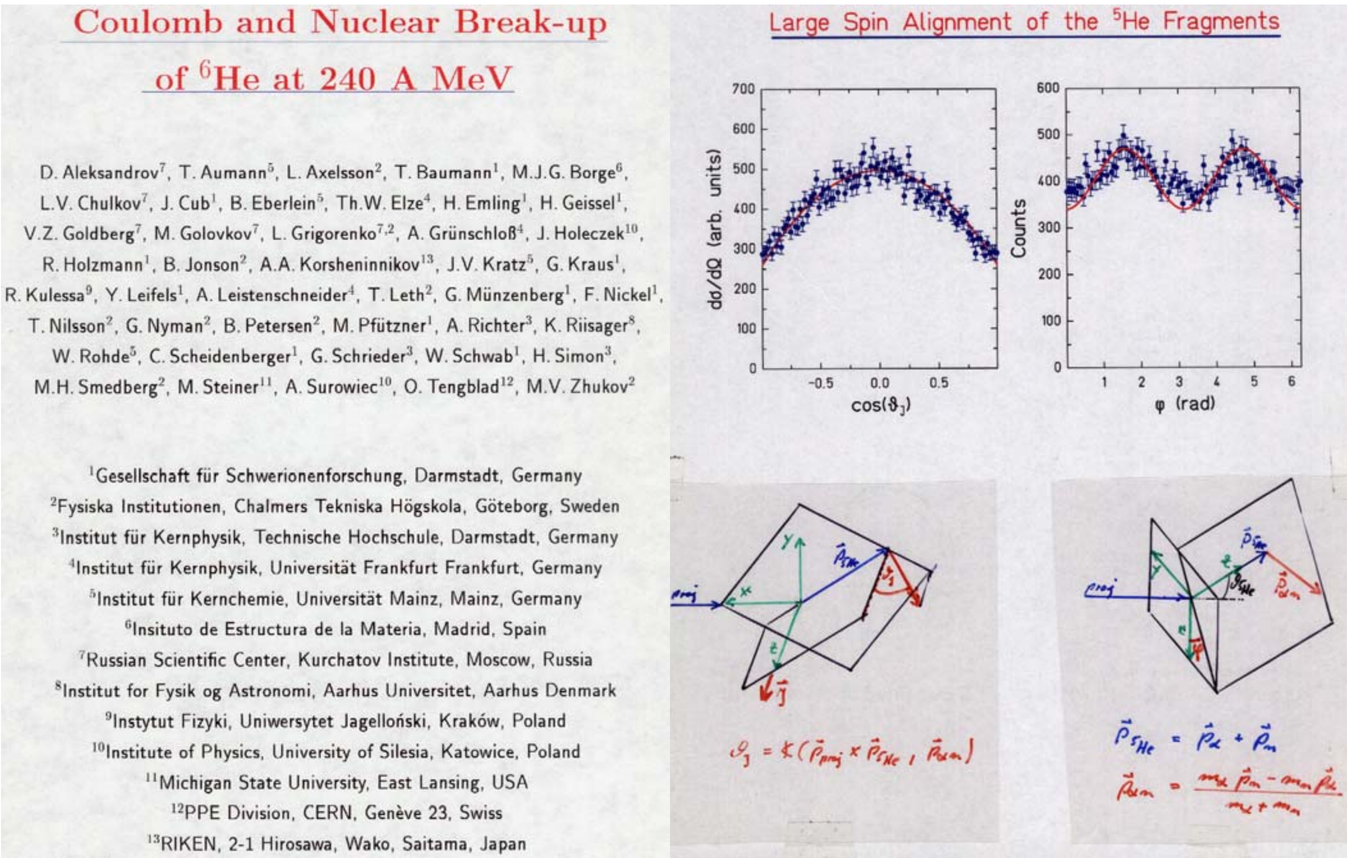
GSI *Darmstadt*

Workshop: The Physics of Halo Nuclei, Halo 06, Trento, October 30th 2006

- Coulomb breakup – spectroscopy and astrophysics
- Comparison of different methods
- Outlook: new experiments

Trento 1996

Workshop on the Physics of Halo Nuclei



Coulomb and Nuclear Break-up of ^6He at 240 A MeV

D. Aleksandrov[7], T. Aumann[5], L. Axelsson[2], T. Baumann[1], M.J.G. Borge[6], L.V. Chulkov[7], J. Cub[1], B. Eberlein[5], Th.W. Elze[4], H. Emling[1], H. Geissel[1], V.Z. Goldberg[7], M. Golovkov[7], L. Grigorenko[7,2], A. Grünschloß[4], J. Holeczek[10], R. Holzmann[1], B. Jonson[2], A.A. Korsheninnikov[13], J.V. Kratz[5], G. Kraus[1], R. Kulessa[9], Y. Leifels[1], A. Leistenschneider[4], T. Leth[2], G. Münzenberg[1], F. Nickel[1], T. Nilsson[2], G. Nyman[2], B. Petersen[2], M. Pfützner[1], A. Richter[3], K. Riisager[8], W. Rohde[5], C. Scheidenberger[1], G. Schrieder[3], W. Schwab[1], H. Simon[3], M.H. Smedberg[2], M. Steiner[11], A. Surowiec[10], O. Tengblad[12], M.V. Zhukov[2]

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At ECT*, Trento, October 7 - 17 1996
Organized by

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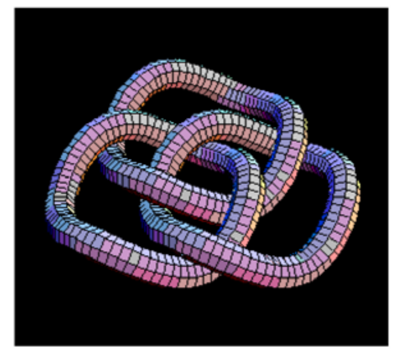


GSI Exp. S135

(Oct '95)

B. Jonson et al.

Trento 2006

2006

Workshop on the Physics of Halo Nuclei

10 years later

Haik SImon

2006

Systematic investigation of the drip-line nuclei ^{11}Li and ^{14}Be and their unbound subsystems ^{10}Li and ^{13}Be
H. Simon *et al.*,
Nucl. Phys. A, in preparation

2005

Three-body correlations in electromagnetic dissociation of Borromean nuclei: The ^{6}He case
L.V. Chulkov, H. Simon, I.J. Thompson, T. Aumann, M.J.G. Borge, Th.W. Elze, H. Emling, H. Geissel, L.V. Grigorenko, M Hellström, B. Jonson, J.V. Kratz, R. Kulessa, K. Markenroth, M. Meister, G. Münzenberg, F. Nickel, T. Nilsson, G. Nyman, V. Pribora, A. Richter, K. Riisager, C. Scheidenberger, G. Schrieder, O. Tengblad, M.V. Zhukov,
Nucl. Phys. A **759** (2005) [illegible]

2004

Two- and three-body correlations: breakup of halo nuclei
H. Simon, T. Aumann, M.J.G. Borge, L.V. Chulkov, Th.W. Elze, H. Emling, C. Forssén, H. Geissel, M. Hellström, B. Jonson, J.V. Kratz, R. Kulessa, Y. Leifels, K. Markenroth, M. Meister, G. Münzenberg, F. Nickel, T. Nilsson, G. Nyman, V. Pribora, A. Richter, K. Riisager, C. Scheidenberger, G. Schrieder, O. Tengblad and M.V. Zhukov,
Nucl. Phys. A **734** (2004) 323.

2003

On the $t+n+n$ system and ^{5}H
M. Meister, L.V. Chulkov, H. Simon, T. Aumann, M.J.G. Borge, W. Dostal, Th.W. Elze, H. Emling, H. Geissel, M. Hellström, B. Jonson, J.V. Kratz, R. Kulessa, Y. Leifels, K. Markenroth, G. Münzenberg, F. Nickel, T. Nilsson, G. Nyman, V. Pribora, A. Richter, K. Riisager, C. Scheidenberger, G. Schrieder, O. Tengblad and M.V. Zhukov,
Phys. Rev. Lett. **91** (2003) 162504.

Searching for the ^{5}H resonance in the $t+n+n$ system
M. Meister, L.V. Chulkov, H. Simon, T. Aumann, M.J.G. Borge, W. Dostal, Th.W. Elze, H. Emling, H. Geissel, M. Hellström, B. Jonson, J.V. Kratz, R. Kulessa, Y. Leifels, K. Markenroth, G. Münzenberg, F. Nickel, T. Nilsson, G. Nyman, V. Pribora, A. Richter, K. Riisager, C. Scheidenberger, G. Schrieder, O. Tengblad,
Nucl. Phys. A **723** (2003) 13.

2002

Evidence for a new low-lying resonance in ^{7}He
M. Meister, K. Markenroth, D. Aleksandrov, T. Aumann, L. Axelsson, T. Baumann, M.J.G. Borge, L.V. Chulkov, W. Dostal, B. Eberlein, Th.W. Elze, H. Emling, C. Forssén, H. Geissel, M. Hellström, R. Holzmann, B. Jonson, J.V. Kratz, R. Kulessa, Y. Leifels, A. Leistenschneider, I. Mukha, G. Münzenberg, F. Nickel, T. Nilsson, G. Nyman, A. Richter, K. Riisager, C. Scheidenberger, G. Schrieder, H. Simon, O. Tengblad and M.V. Zhukov,
Phys. Rev. Lett. **88** (2002) 102501.

^{8}He–^{6}He: a comparative study of electromagnetic fragmentation reactions
M. Meister, K. Markenroth, D. Aleksandrov, T. Aumann, T. Baumann, M.J.G. Borge, L.V. Chulkov, D. Cortina-Gil, B. Eberlein, Th.W. Elze, H. Emling, H. Geissel, M. Hellström, B. Jonson, J.V. Kratz, R. Kulessa, A. Leistenschneider, I. Mukha, G. Münzenberg, F. Nickel, T. Nilsson, G. Nyman, M. Pfützner, V. Pribora, A. Richter, K. Riisager, C. Scheidenberger, G. Schrieder, H. Simon, O. Tengblad and M.V. Zhukov,
Nucl. Phys. A **700** (2002) 3.

2001

^{8}He–^{6}He: a comparative study of nuclear fragmentation reactions
K. Markenroth, M. Meister, B. Eberlein, D. Aleksandrov, T. Aumann, L. Axelsson, T. Baumann, M.J.G. Borge, L.V. Chulkov, W. Dostal, Th.W. Elze, H. Emling, H. Geissel, A. Grünschloß, M. Hellström, J. Holeczek, B. Jonson, J.V. Kratz, G. Kraus, R. Kulessa, A. Leistenschneider, I. Mukha, G. Münzenberg, F. Nickel, T. Nilsson, G. Nyman, M. Pfützner, V. Pribora, A. Richter, K. Riisager, C. Scheidenberger, G. Schrieder, H. Simon, J. Stroth, O. Tengblad and M.V. Zhukov,
Nucl. Phys. A **679** (2001) 462.

2000

Halo excitations in fragmentation of ^{6}He at 240 MeV/u on carbon and lead targets
D. Aleksandrov, T. Aumann, L. Axelsson, T. Baumann, M.J.G. Borge, L.V. Chulkov, J. Cub, W. Dostal, B. Eberlein, Th.W. Elze, H. Emling, H. Geissel, V.Z. Goldberg, M. Golovkov, A. Grünschloß, M. Hellström, K. Hencken, J. Holeczek, R. Holzmann, B. Jonson, A.A. Korsheninnikov, J.V. Kratz, G. Kraus, R. Kulessa, Y. Leifels, A. Leistenschneider, T. Leth, I. Mukha, G. Münzenberg, F. Nickel, T. Nilsson, G. Nyman, B. Petersen, M. Pfützner, A. Richter, K. Riisager, C. Scheidenberger, G. Schrieder, W. Schwab, H. Simon, M.H. Smedberg, M. Steiner, J. Stroth, A. Surowiec, T. Suzuki, O. Tengblad and M.V. Zhukov,
Nucl. Phys. A **669** (2000) 51.

1999

Direct experimental evidence for strong admixture of different parity states in ^{11}Li
H. Simon, D. Aleksandrov, T. Aumann, L. Axelsson, T. Baumann, M.J.G. Borge, L.V. Chulkov, R. Collatz, J. Cub, W. Dostal, B. Eberlein, Th.W. Elze, H. Emling, H. Geissel, A. Grünschloß, M. Hellström, J. Holeczek, R. Holzmann, B. Jonson, J.V. Kratz, G. Kraus, R. Kulessa, Y. Leifels, A. Leistenschneider, T. Leth, I. Mukha, G. Münzenberg, F. Nickel, T. Nilsson, G. Nyman, B. Petersen, M. Pfützner, A. Richter, K. Riisager, C. Scheidenberger, G. Schrieder, W. Schwab, M.H. Smedberg, J. Stroth, A. Surowiec, O. Tengblad and M.V. Zhukov,
Phys. Rev. Lett. **83** (1999) 496.

Continuum Excitations in ^{6}He
T. Aumann, D. Aleksandrov, L. Axelsson, T. Baumann, M.J.G. Borge, L.V. Chulkov, J. Cub, W. Dostal, B. Eberlein, Th.W. Elze, H. Emling, H. Geissel, V.Z. Goldberg, M. Golovkov, A. Grünschloß, M. Hellström, K. Hencken, J. Holeczek, R. Holzmann, B. Jonson, A.A. Korsheninnikov, J.V. Kratz, G. Kraus, R. Kulessa, Y. Leifels, A. Leistenschneider, T. Leth, I. Mukha, G. Münzenberg, F. Nickel, T. Nilsson, G. Nyman, B. Petersen, M. Pfützner, A. Richter, K. Riisager, C. Scheidenberger, G. Schrieder, W. Schwab, H. Simon, M.H. Smedberg, M. Steiner, J. Stroth, A. Surowiec, T. Suzuki, O. Tengblad and M.V. Zhukov,
Phys. Rev. C **59** (1999) 1252.

1998

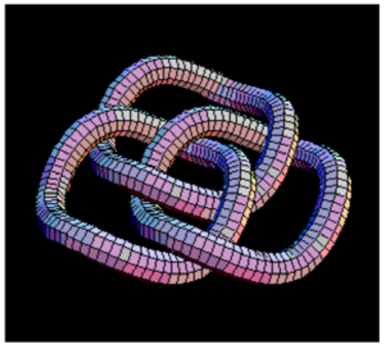
Manifestation of the Halo Structure in Momentum Distributions from ^{6}He Fragmentation
T. Aumann, L.V. Chulkov, V.N. Pribora, M.H. Smedberg,
Nucl. Phys. A **640** (1998) 24.

Invariant Mass Spectrum and $\alpha - n$ Correlation Function studied in the Fragmentation of ^{6}He on a Carbon Target
D. Aleksandrov, T. Aumann, L. Axelsson, T. Baumann, M.J.G. Borge, L.V. Chulkov, J. Cub, W. Dostal, B. Eberlein, Th.W. Elze, H. Emling, H. Geissel, V.Z. Goldberg, M. Golovkov, A. Grünschloss, M Hellström, J. Holeczek, R. Holzmann, B. Jonson, A.A. Korsheninnikov, J.V. Kratz, G. Kraus, R. Kulessa, Y. Leifels, A. Leistenschneider, T. Leth, I. Mukha, G. Münzenberg, F. Nickel, T. Nilsson, G. Nyman, B. Petersen, M. Pfützner, A. Richter, K. Riisager, C. Scheidenberger, G. Schrieder, W. Schwab, H. Simon, M.H. Smedberg, M. Steiner, J. Stroth, A. Surowiec, T. Suzuki, O. Tengblad and M.V. Zhukov,
Nucl. Phys. A **633** (1998) 234.

1997

Large Spin Alignment of the Unbound ^{5}He Fragment after Fragmentation of 240 MeV/nucleon ^{6}He
L.V. Chulkov, T. Aumann, D. Aleksandrov, L. Axelsson, T. Baumann, M.J.G. Borge, R. Collatz, J. Cub, W. Dostal, B. Eberlein, Th.W. Elze, H. Emling, H. Geissel, V.Z. Goldberg, M. Golovkov, A. Grünschloss, M. Hellström, J. Holeczek, R. Holzmann, B. Jonson, A.A. Korsheninnikov, J.V. Kratz, G. Kraus, R. Kulessa, Y. Leifels, A. Leistenschneider, T. Leth, I. Mukha, G. Münzenberg, F. Nickel, T. Nilsson, G. Nyman, B. Petersen, M. Pfützner, A. Richter, K. Riisager, C. Scheidenberger, G. Schrieder, W. Schwab, H. Simon, M.H. Smedberg, M. Steiner, J. Stroth, A. Surowiec, T. Suzuki and O. Tengblad,
Phys. Rev. Lett. **79** (1997) 201.

!996

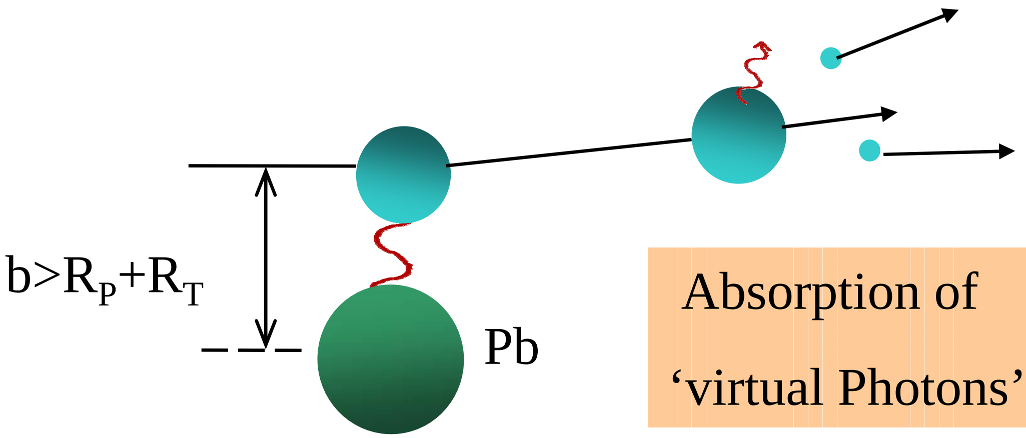


GSI Exp. S135

(Oct '95)

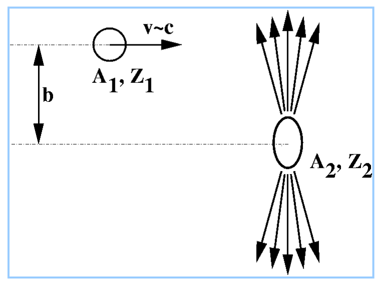
B. Jonson et al.

Experimental Approach:
Electromagnetic excitation at high energies



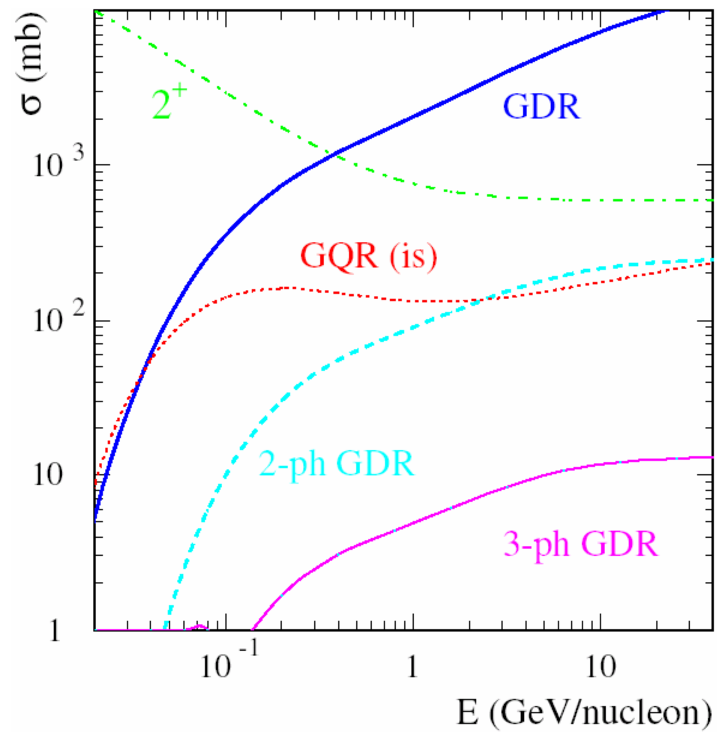
$\sigma_{elm} \sim Z^2$

Absorption of 'virtual Photons'



Semi-classical theory:

$$d\sigma_{elm} / dE = N_\gamma(E)\, \sigma_\gamma(E)$$

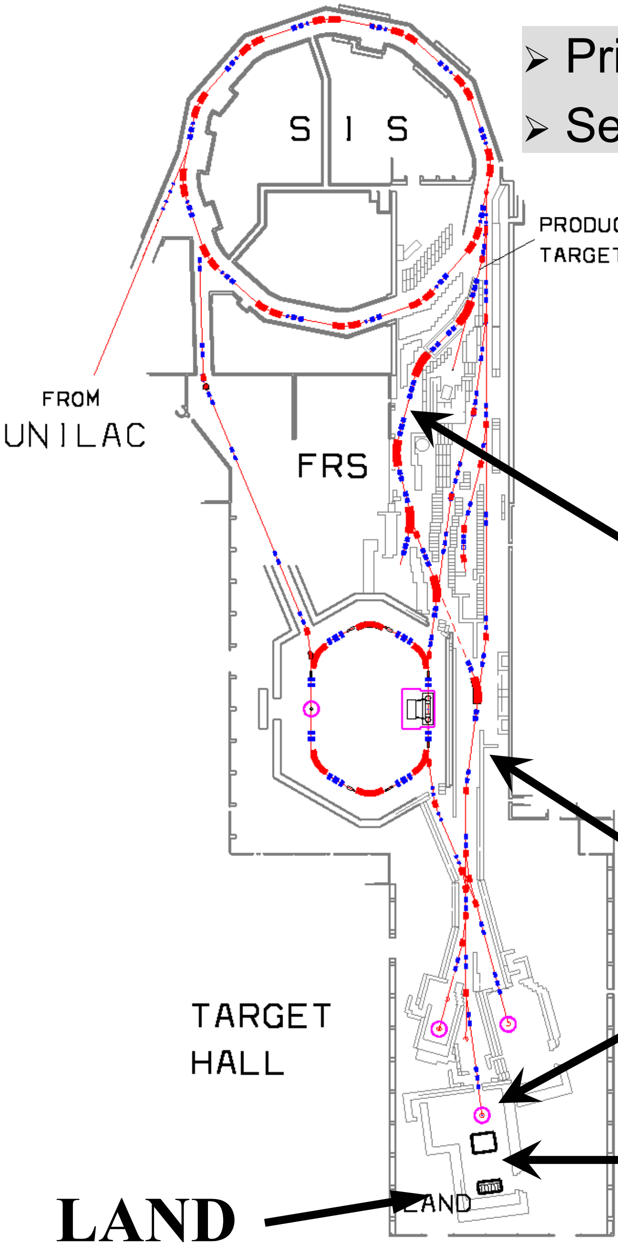


High velocities $v/c \approx 0.6$-0.9
$\Rightarrow$ High-frequency Fourier components
$E_{\gamma,max} \approx 25$ MeV (@ 1 GeV/u)

Determination of 'photon energy' (excitation energy) via a kinematically complete measurement of the momenta of all outgoing particles (invariant mass)

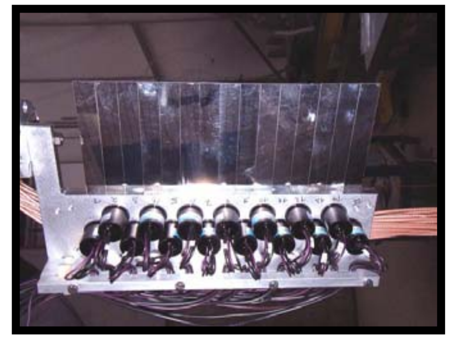
Experimental Approach: Production of (fission-)fragment beams

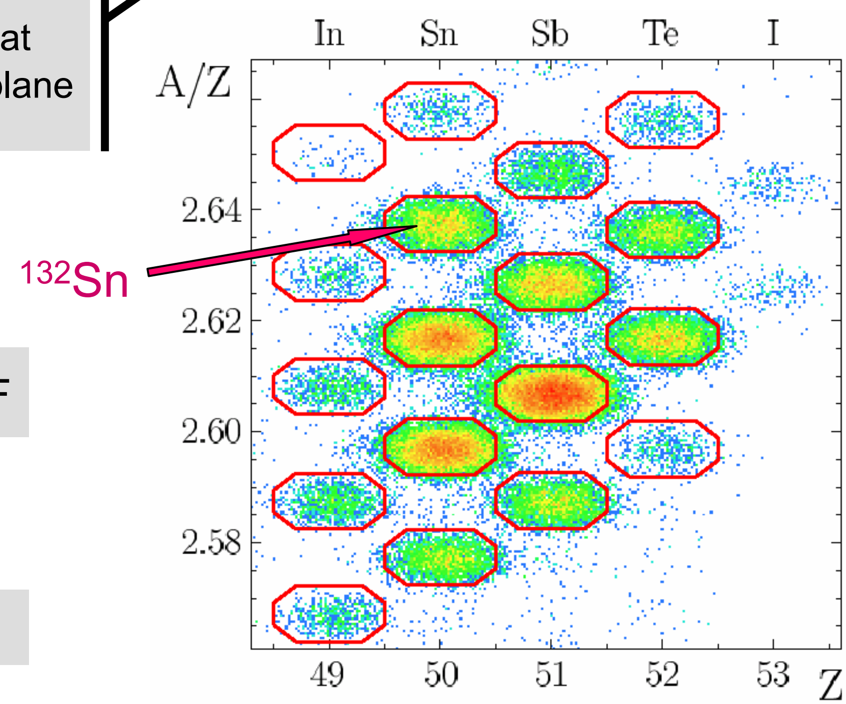
- Primary: 3*10^8 ^{238}U/spill @550MeV/u
- Secondary (mixed): 50 ions ^{132}Sn/spill (~10/sec @500 MeV/u)



$$\frac{A}{Z} = \frac{e}{m_u c} \frac{B\rho}{\beta\gamma}$$

Bρ – from position at middle focal plane of the FRS

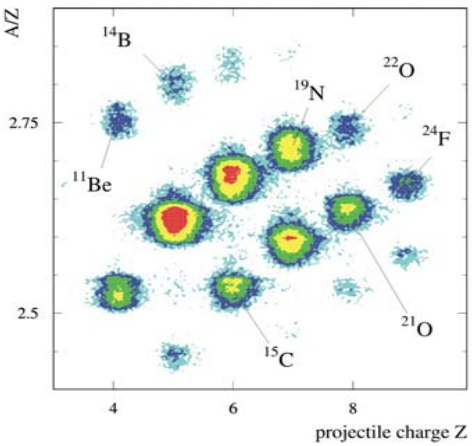


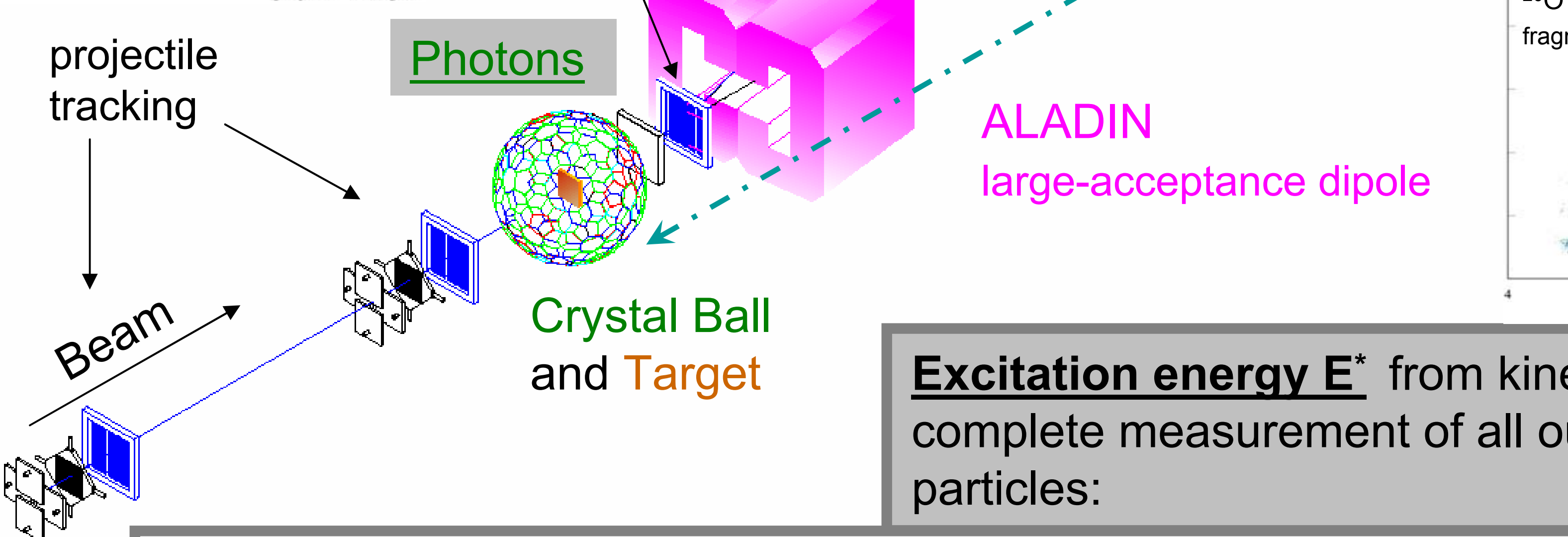


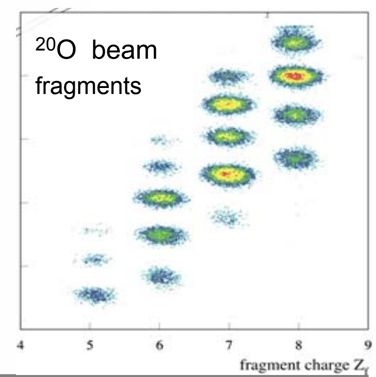
β – from TOF

Z – from ΔE

The LAND reaction setup @GSI







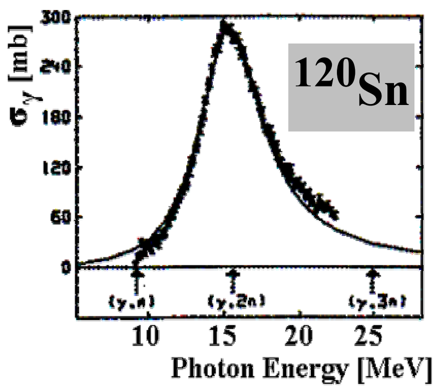
Excitation energy E* from kinematically complete measurement of all outgoing particles:

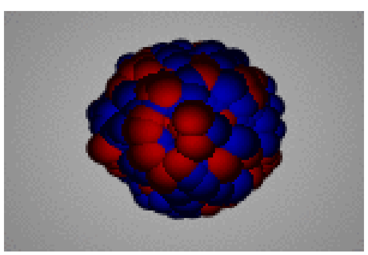
$$E^* = \left(\sqrt{\sum_i m_i^2 + \sum_{i\neq j} m_i m_j \gamma_i \gamma_j (1-\beta_i\beta_j \cos\theta_{ij})} - m_{proj}\right)c^2 + E_\gamma$$

The dipole response of neutron-rich nuclei

Stable nuclei:

100% of the E1 strength absorbed into the **Giant Dipole Resonance** (GDR)



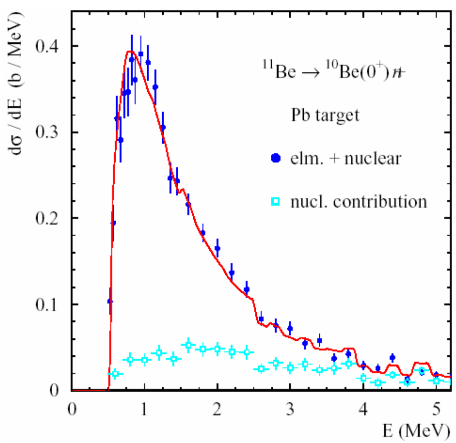


Neutron-Proton asymmetric nuclei: low-lying dipole strength

! threshold strength

non-resonant transitions

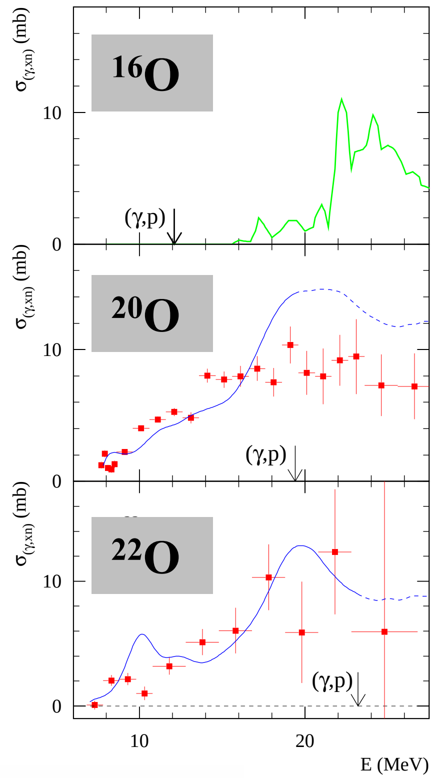
The one-neutron Halo ^{11}Be



spectroscopic tool:

$$\frac{d\sigma}{dE^*}(I_c^\pi) = (\frac{16\pi^3}{9\hbar c})N_{E1}(E^*)\sum_{nlj} C^2 S(I_c^\pi, n\ell j)$$
$$\times \sum_m |\langle \boldsymbol{q}|(Ze/A)rY_m^1|\phi_{n\ell j}(r)\rangle|^2.$$

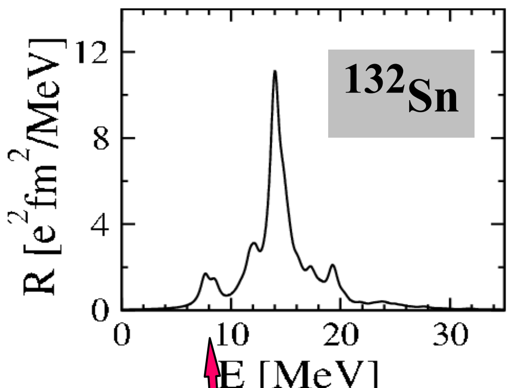
! strong fragmentation

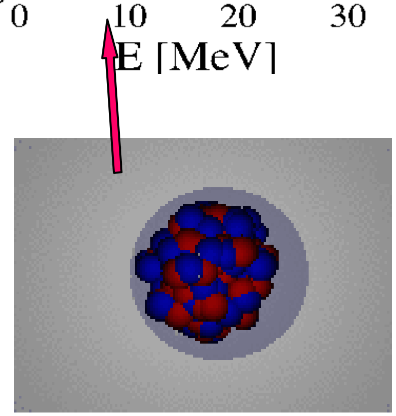


? new collective soft dipole mode

(Pygmy resonance)

Prediction: RMF (N. Paar et al.)



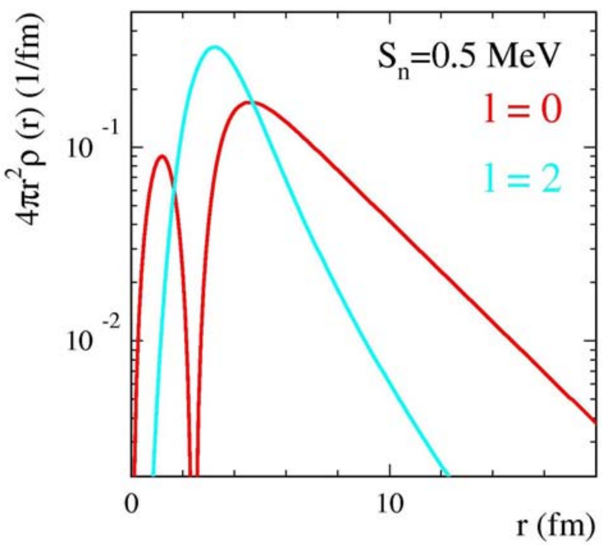


Low-lying E1 strength as spectroscopic tool

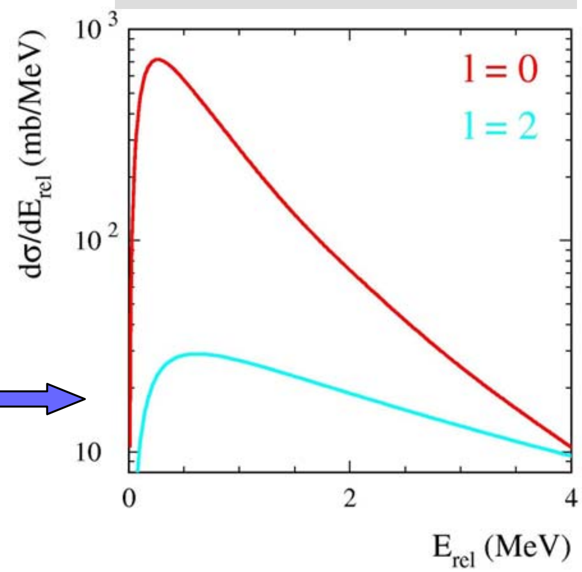
Wave function: e.g. $|^{11}Be\rangle = \alpha|^{10}Be(0^+)\otimes 2s_{1/2}\rangle + \beta|^{10}Be(2^+)\otimes 1d_{5/2}\rangle + \ldots$

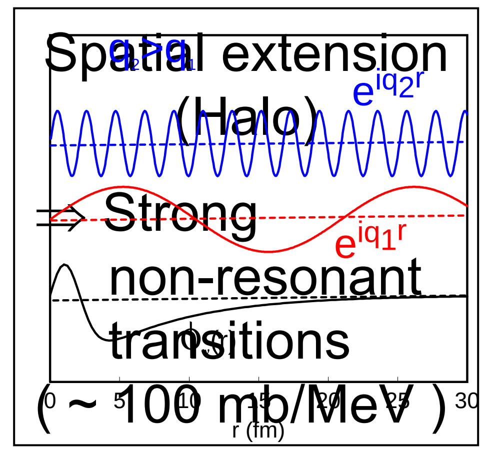
$$d\sigma(I_c^\pi)/dE_{rel} = \frac{16\pi^3}{9\hbar c} N_{E1}(E^*)\, S(I_c^\pi, nlj) \sum_m |\langle q | \frac{Ze}{A} r Y_m^l | \Phi_{nlj} \rangle|^2$$

Density distribution



Differential cross section





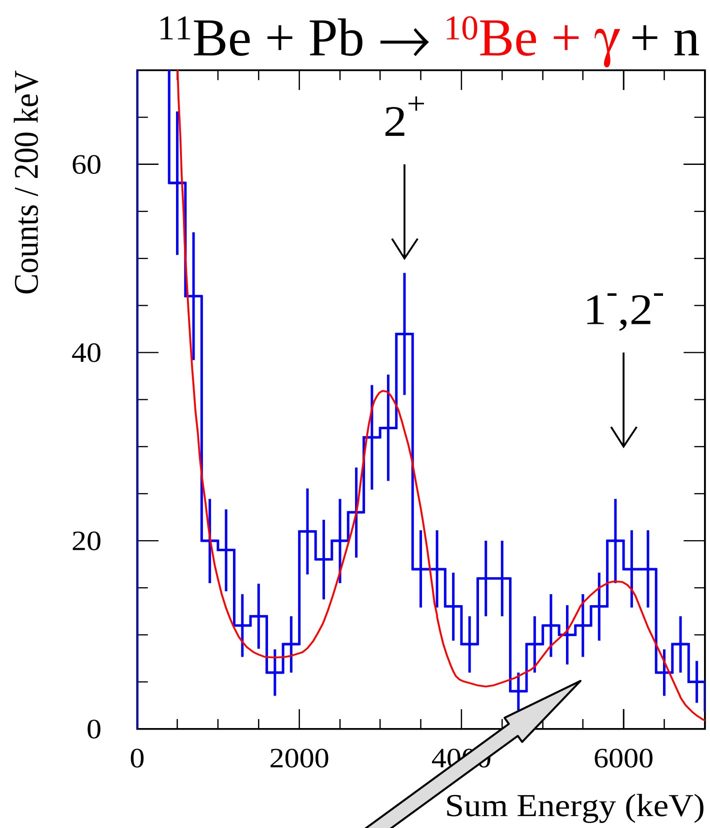
Shape of differential cross section ⇒ angular momentum *l*

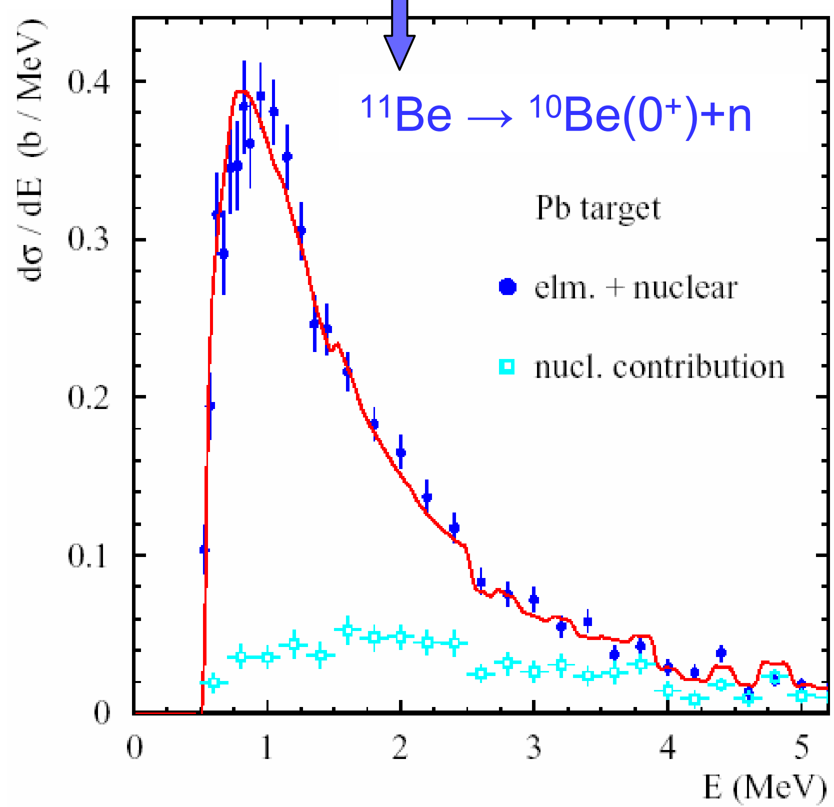
γ-ray coincidence ⇒ identification of core state

Cross section ⇒ spectroscopic factor

Coulomb breakup as spectroscopic tool: The classical one-neutron halo ^{11}Be

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





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

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

Coulomb breakup as spectroscopic tool: The classical one-neutron halo ^{11}Be

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

Spectroscopic factor using a distorted-wave approach:

$S(0^+)=0.61(5)$

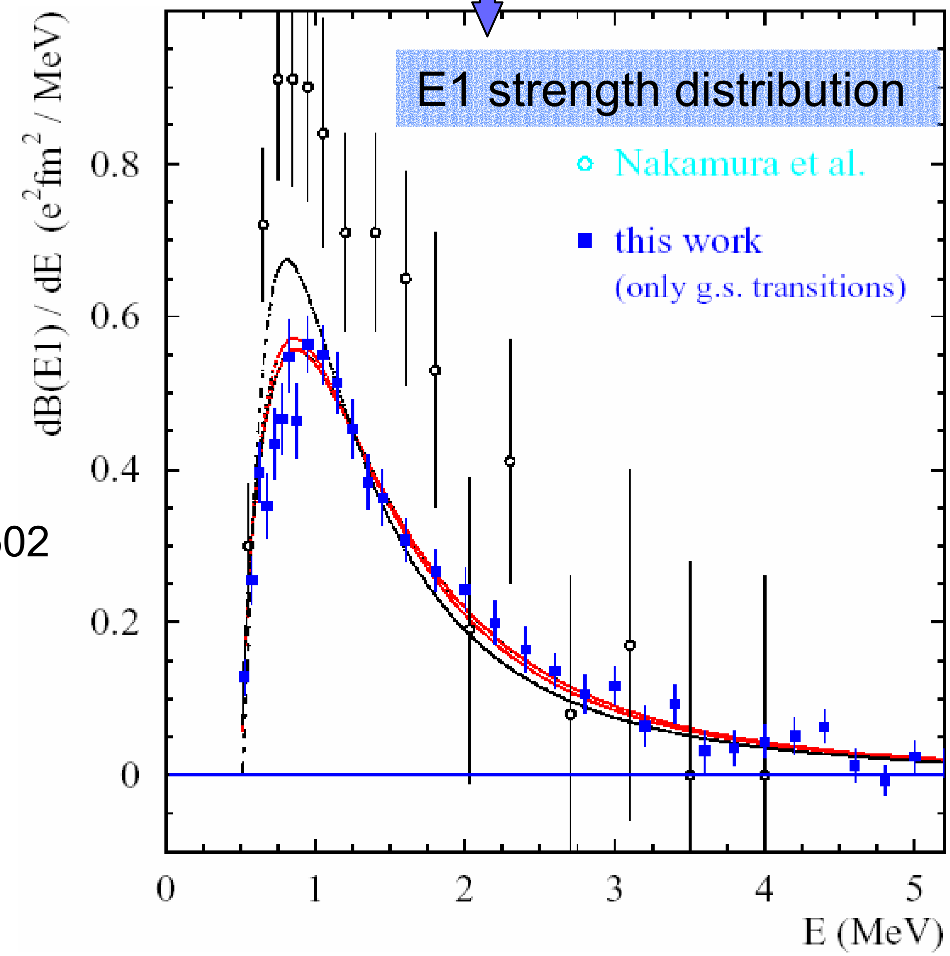
Analysis in the effective range approach:

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

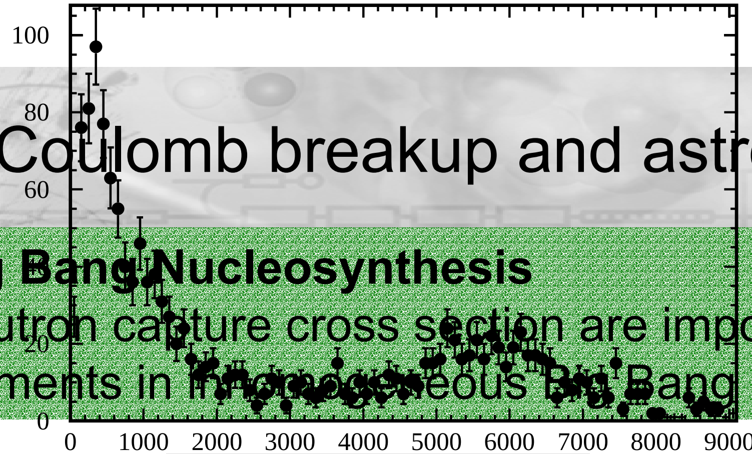
S. Typel, G. Baur, PRL **93** (2004) 142502

Halo radius

$\langle r^2\rangle^{1/2}=5.7(4)$ fm



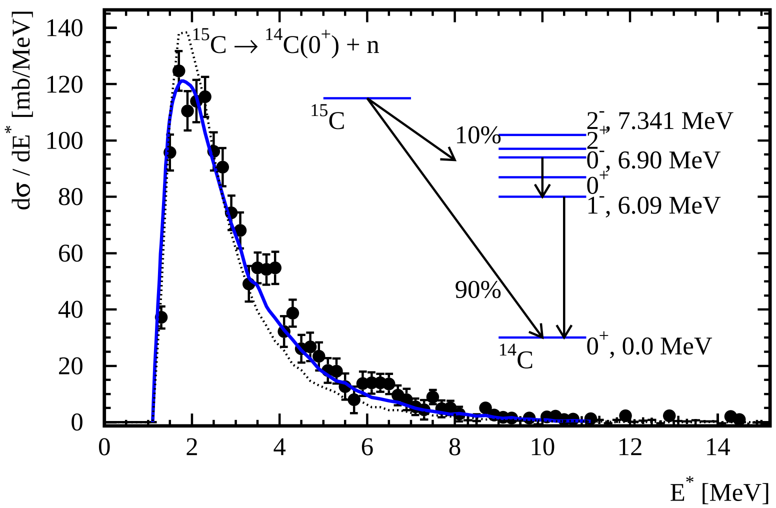
Coulomb breakup and astrophysics – example $^{14}C(n,\gamma)^{15}C$



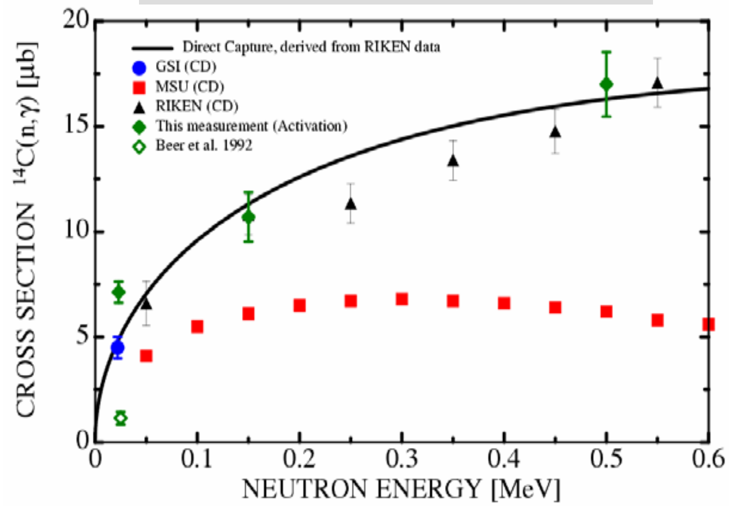
Big Bang Nucleosynthesis

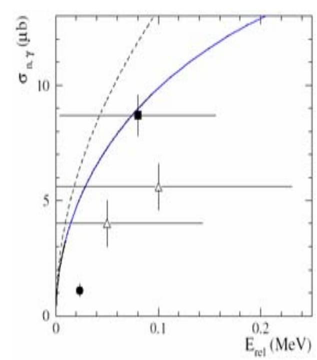
Neutron capture cross section are important for the break-out towards heavier elements in inhomogeneous Big Bang models.

Coulomb breakup



Capture cross section



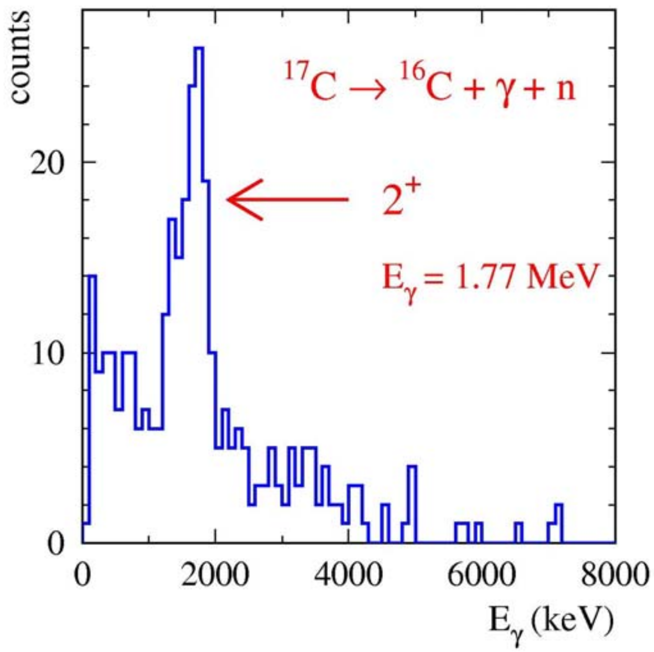


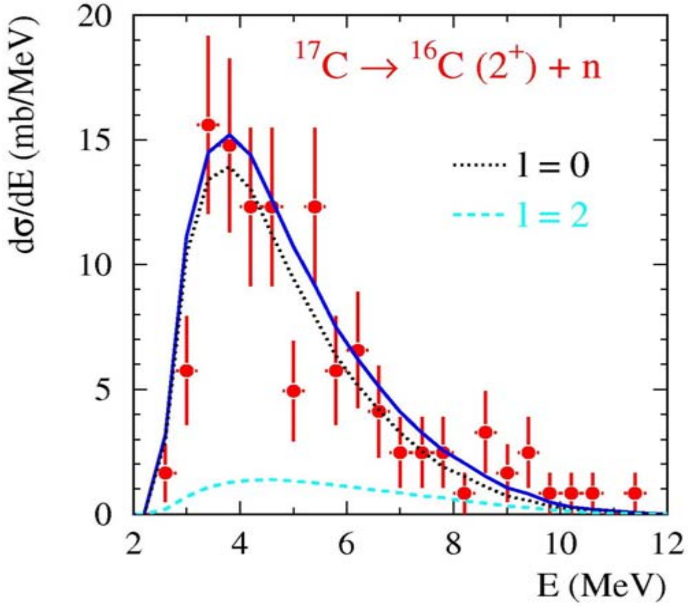
Limitation:

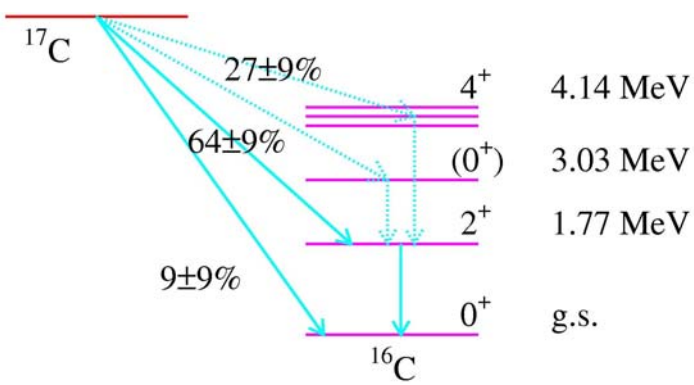
energy-resolution at present not sufficient to measure at very small relative energies

→ R3B: resolution down to 20 keV at ~200keV

Coulomb breakup of ^{17}C







$\Rightarrow$ Dominant ground state configuration

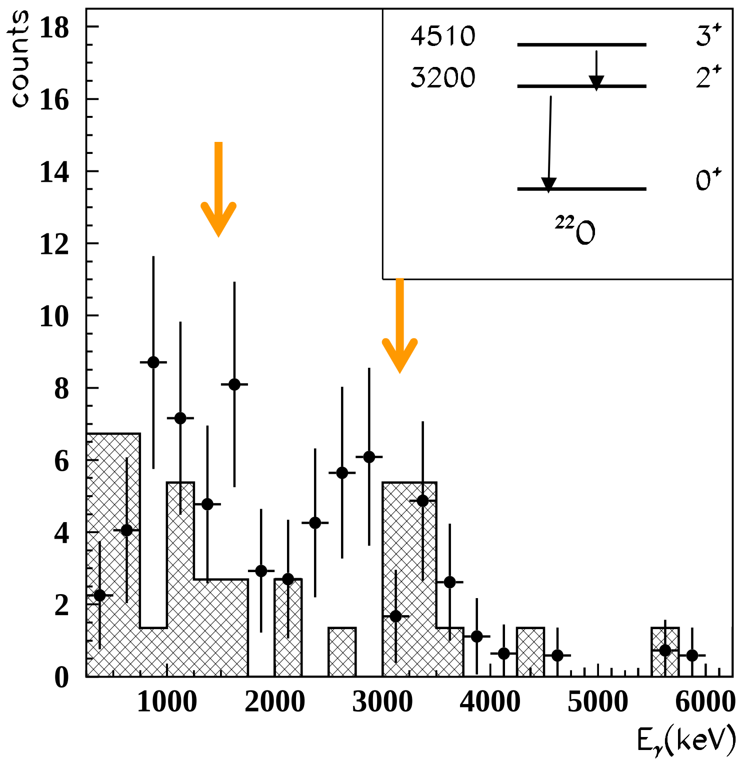
$|{}^{16}C(2^+)\otimes\nu_{s,d}>$

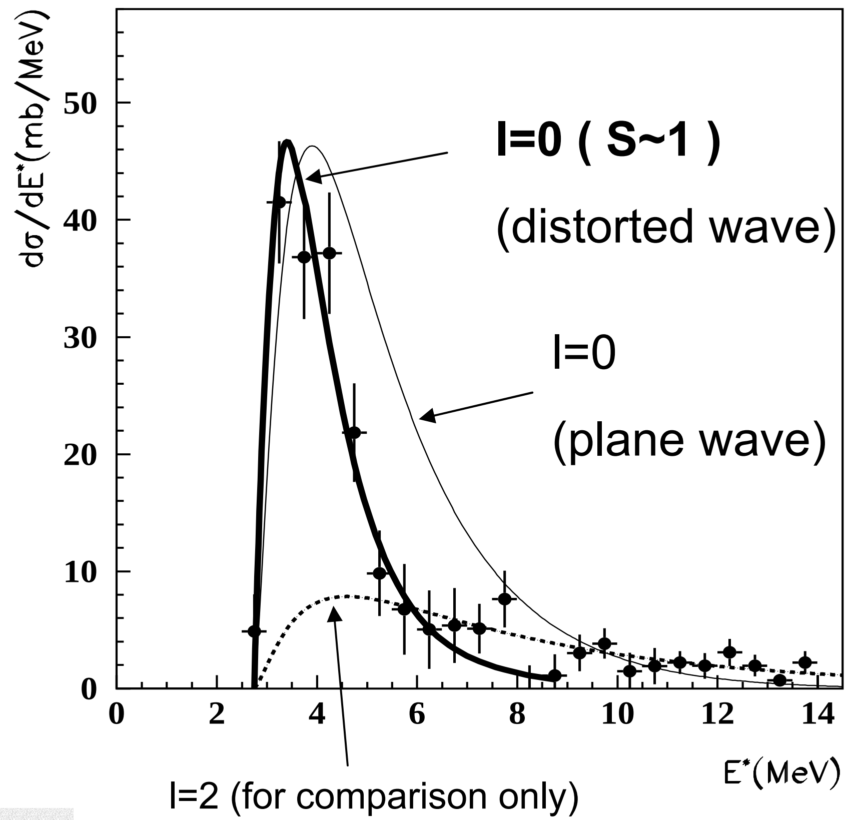
$\Rightarrow$ ground-state spin $I^\pi = 1/2^+$ excluded

Data: LAND-FRS@GSI

U. D. Pramanik et al., Phys. Lett. B 551 (2003) 63

Coulomb breakup as spectroscopic tool: The ground state structure of ^{23}O





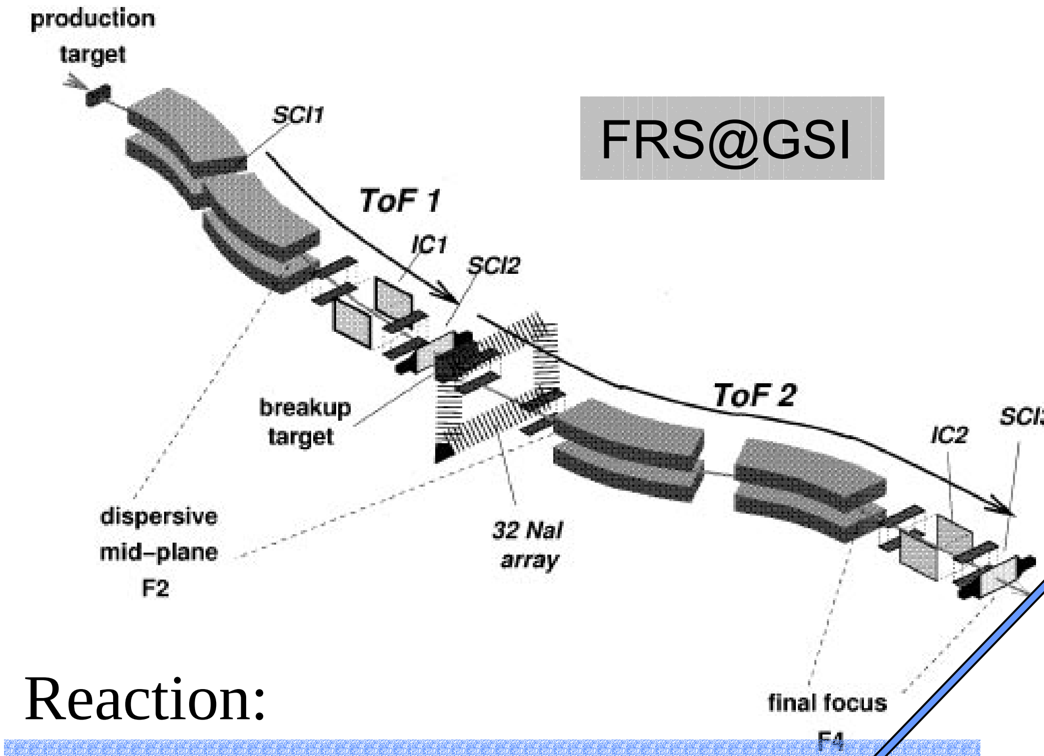
dominant g.s. configuration :

$| ^{22}O(0^+) \otimes \nu_s >$

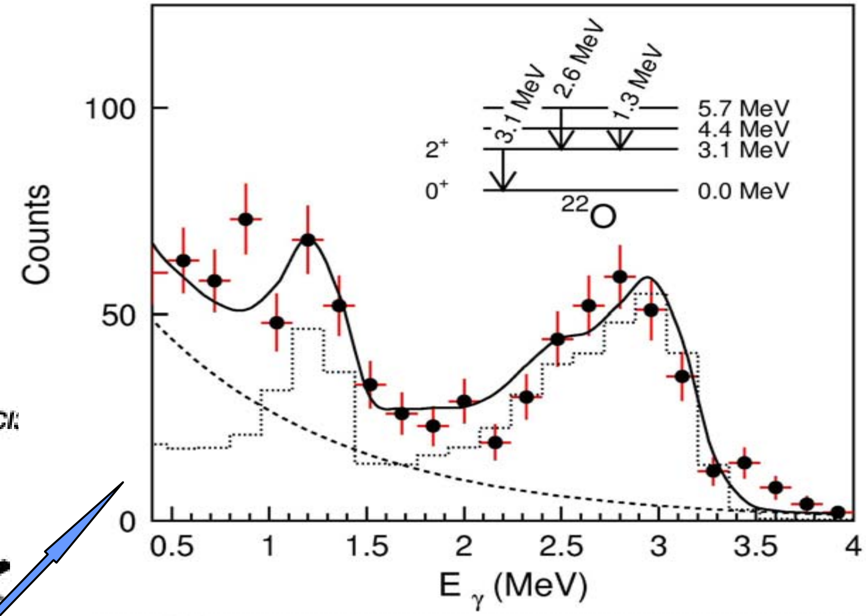
C. Nociforo, K.L. Jones et al., PLB 605 (2005) 23

→ Final state interaction important !

^{23}O: the heaviest halo nucleus?



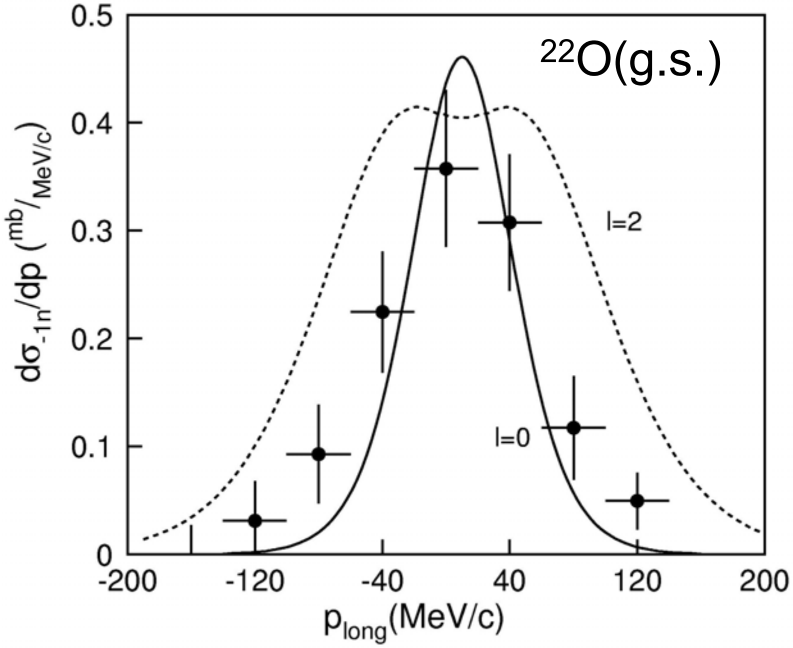
FRS@GSI



Reaction:

^{23}O (938 MeV/u) + C $\rightarrow$ ^{22}O + γ + x

Momentum distribution



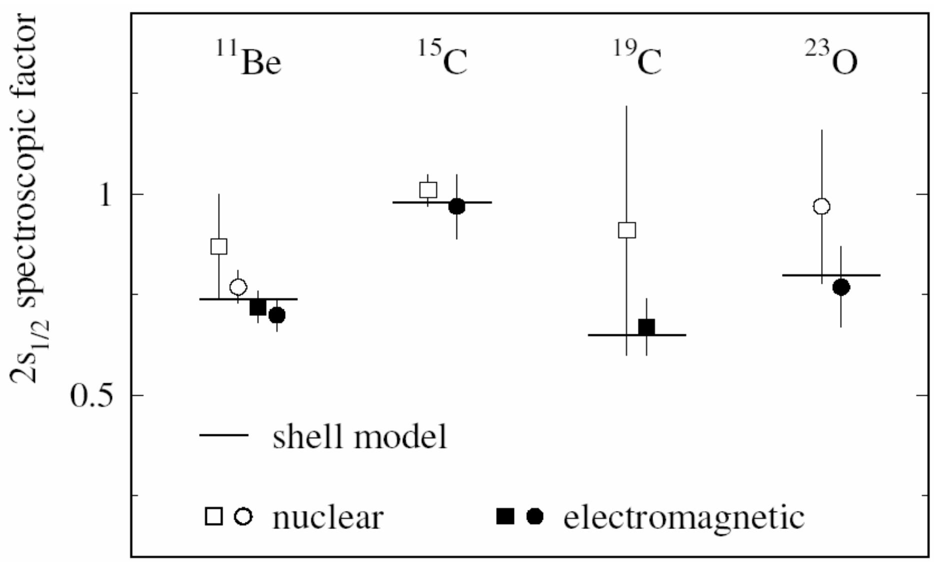
$\Rightarrow$ $I^{\pi} = 1/2^{+}$

$\Rightarrow$ $S\,(\nu_s \otimes {}^{22}O(0^{+})) \approx 0.9(2)$

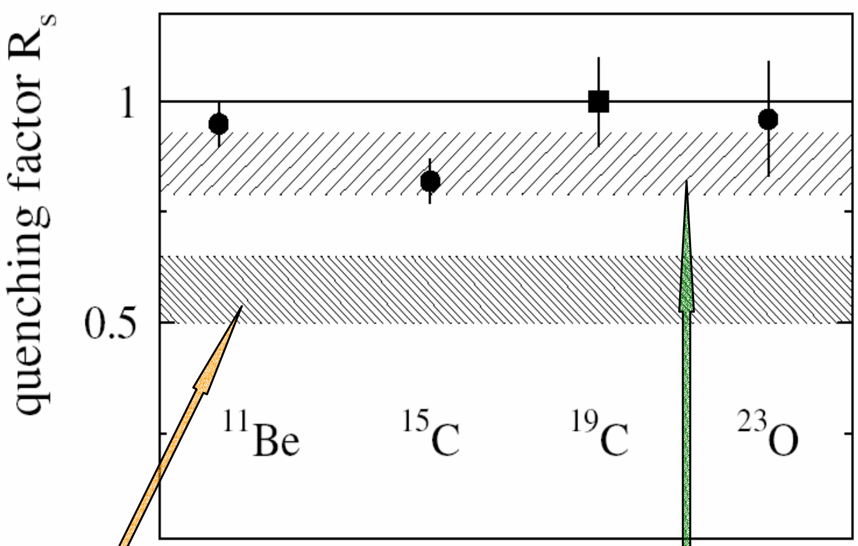
D. Cortina-Gil et al., Phys. Rev. Lett. 93 (2004) 062501

Absolute single-particle occupancies

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-range correlations

Halo states

(almost free nucleons)

Coulomb / Nuclear Breakup

Coulomb breakup

best suited for halo states
(-> huge cross sections)

well understood reaction mechanism
(in particular at high energies)

sensitivity to low-density tail of w.f. (asymptotic normalization)

no parameters in cross section calculations

problem of final state interaction

Knockout + Diffraction

general applicable
(for valence nucleon states)

quantitative reaction theory for knockout part (and for high beam energies)

surface dominated

'core' absorption has to be taken into account (assuming densities)

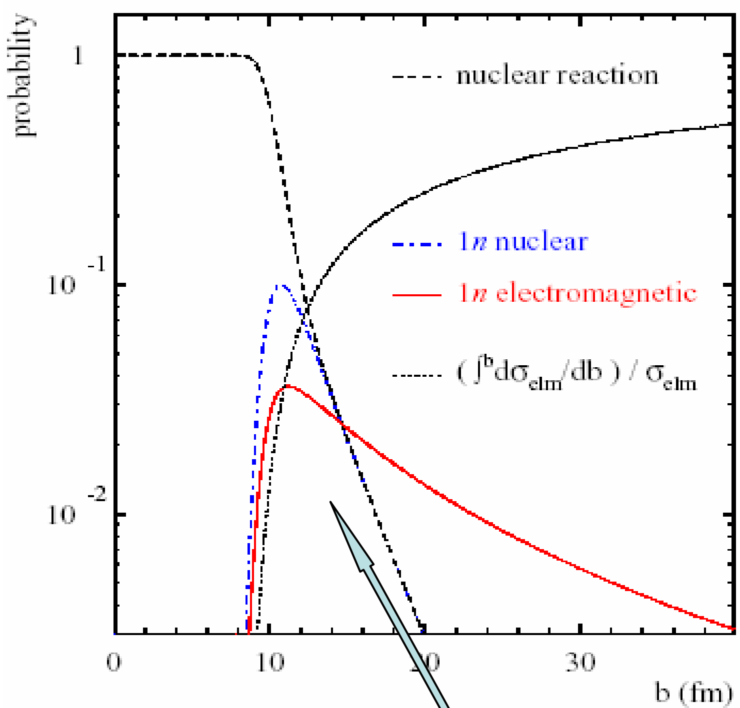
two mechanisms: knockout + diffraction
final state interaction in case of diffraction (resonant excitations)

The two reaction mechanism are complementary and require different approximations in the reaction calculation

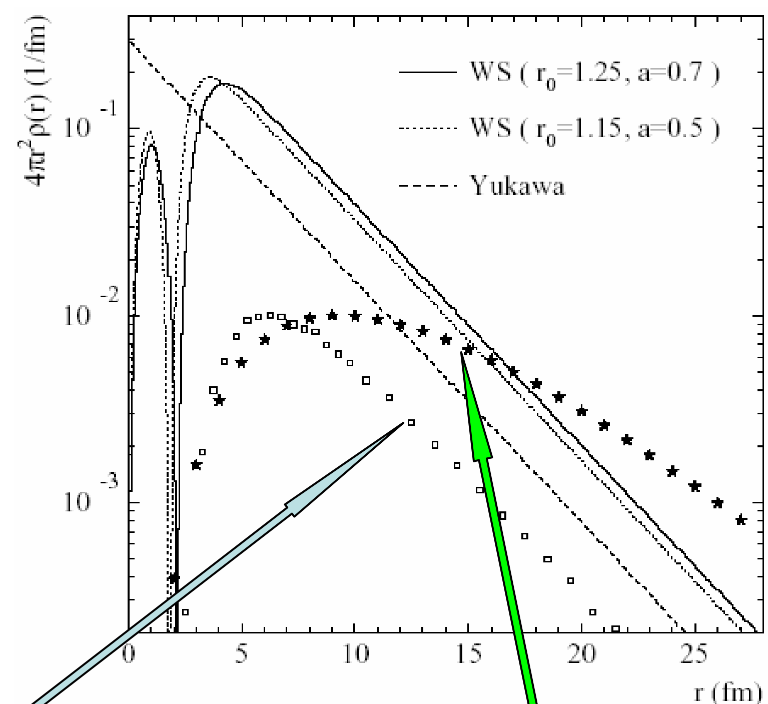
Comparison helps judging how quantitative are spectroscopic factors

Sensitivity of Coulomb and nuclear breakup

Reaction probabilities



Halo-Neutron Densities



Nuclear breakup

Coulomb breakup

Overlap with continuum wave function

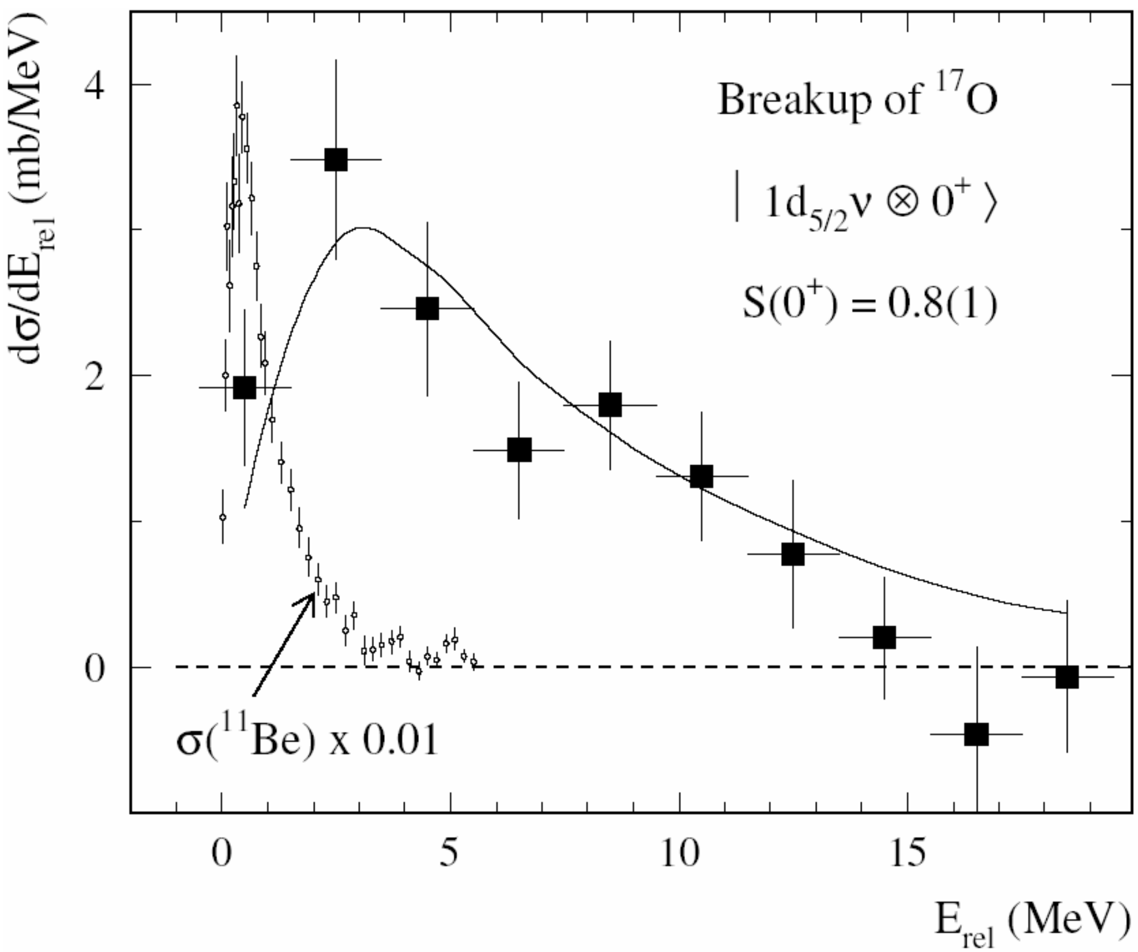
Sensitivity to the tail of the wave function only

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

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

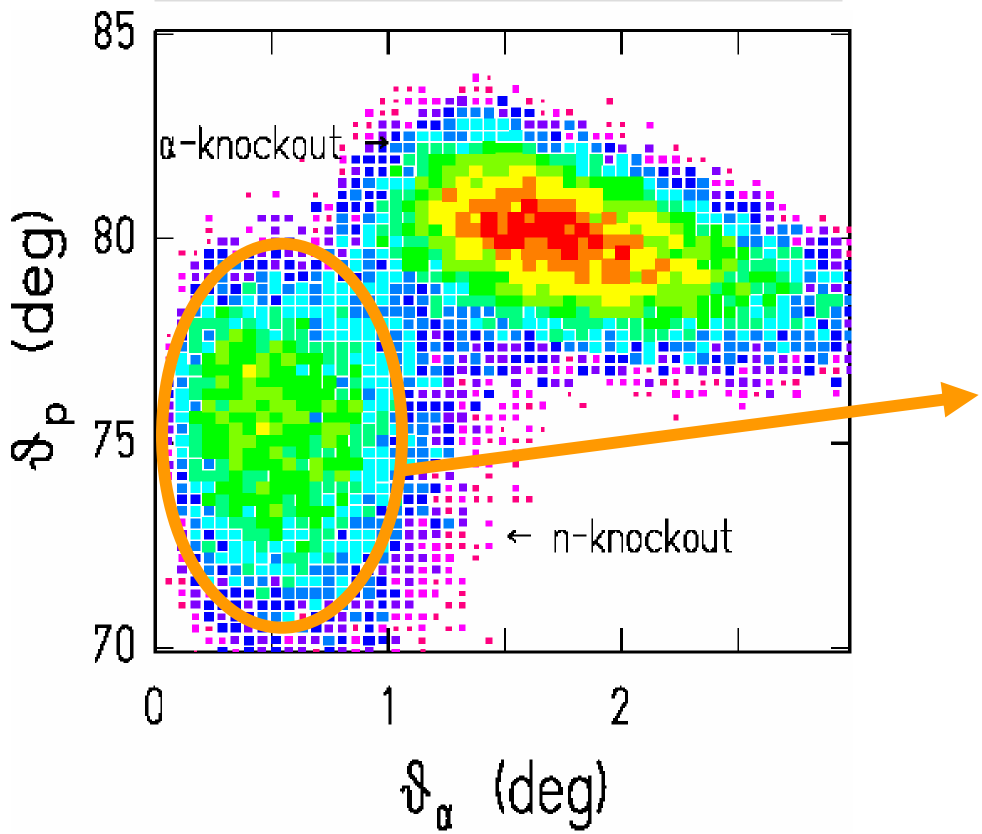
Future: Quasi-free scattering in inverse kinematics

- kinematical complete measurement of
  (p,pn), (p,2p), (p,pd), (p,α), ... reactions
- redundant experimental information:
  kinematical reconstruction from proton momenta
  plus gamma rays, recoil momentum, invariant mass
- sensitivity not limited to surface
  → spectral functions
  → knockout from deeply bound states
- cluster knockout reactions

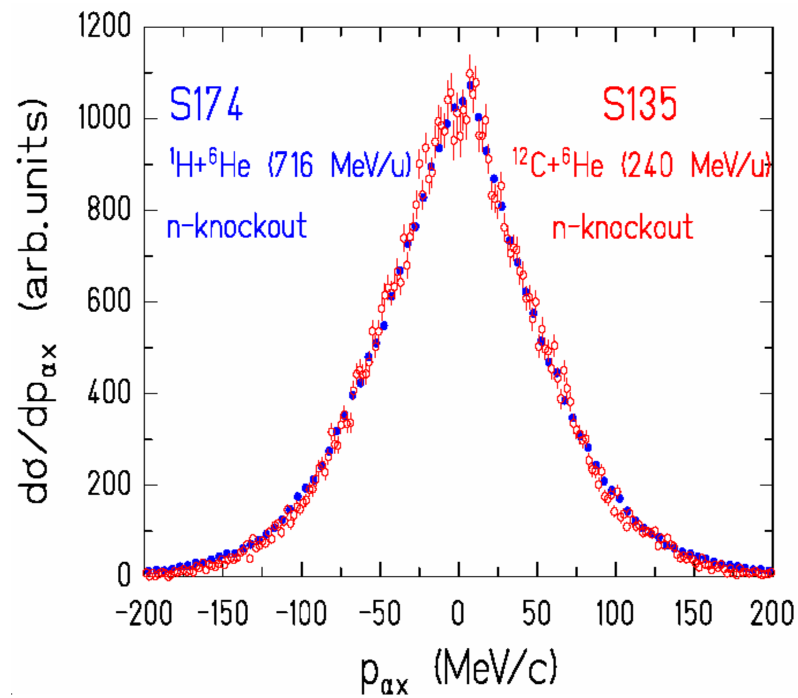
Quasi-free cluster knockout

Experiment S174: Proton elastic scattering (P. Egelhof et al.)

$^6He + p \rightarrow \alpha + p' + X$



Momentum distribution



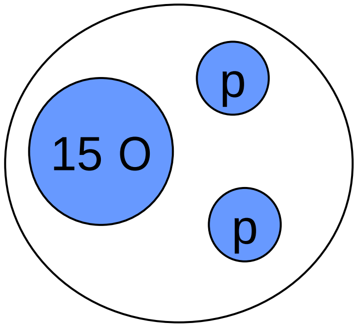
L. Chulkov et al., NPA 759(2005) 43

Spectroscopic factors:

neutron: 1.7(2)

alpha: 0.8(1)

Planned experiment for 2007: The 2p halo ^{17}Ne



- Dripline nucleus
- S_{2p} = 0.95 MeV
- Borromean system: binary sub-systems unbound
- only realistic 2-proton halo candidate

mixture of s^2 and d^2 configurations in the ground-state wave function:

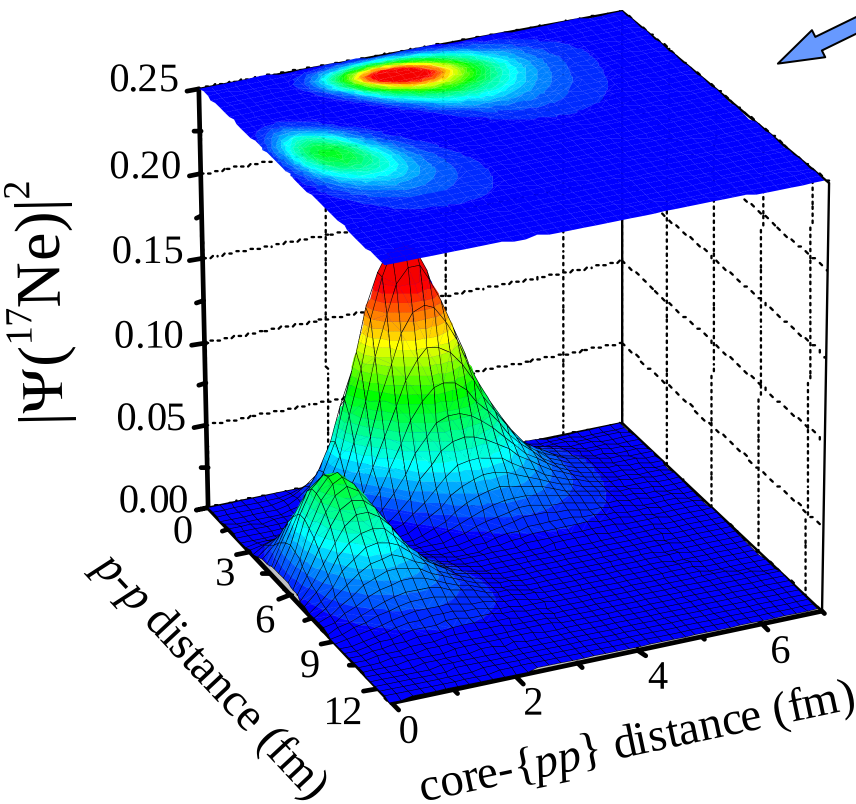
- theoretical prediction vary from dominance of d^2 (no halo) to
  dominance of s^2 configuration (halo formation)

- experimental information does not allow a clear conclusion

  only inclusive data (e.g. momentum distributions, cross sections)
  the proton knockout data (RIKEN) include contributions from knockout of core protons, only the momentum distribution of the A-2 system was measured (inclusively)

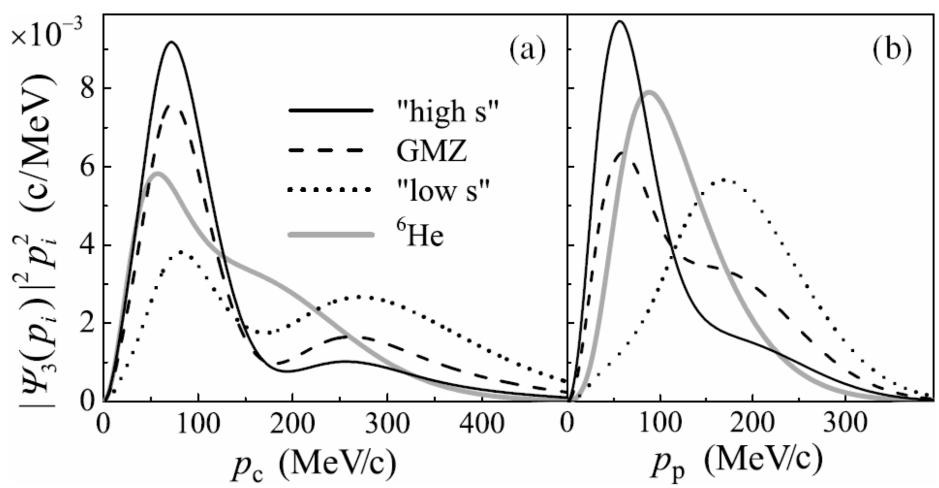
Theoretical predictions: 3-body model

L.V. Grigorenko, I.G. Mukha, M.V. Zhukov, Nucl. Phys. A 713 (2003) 372

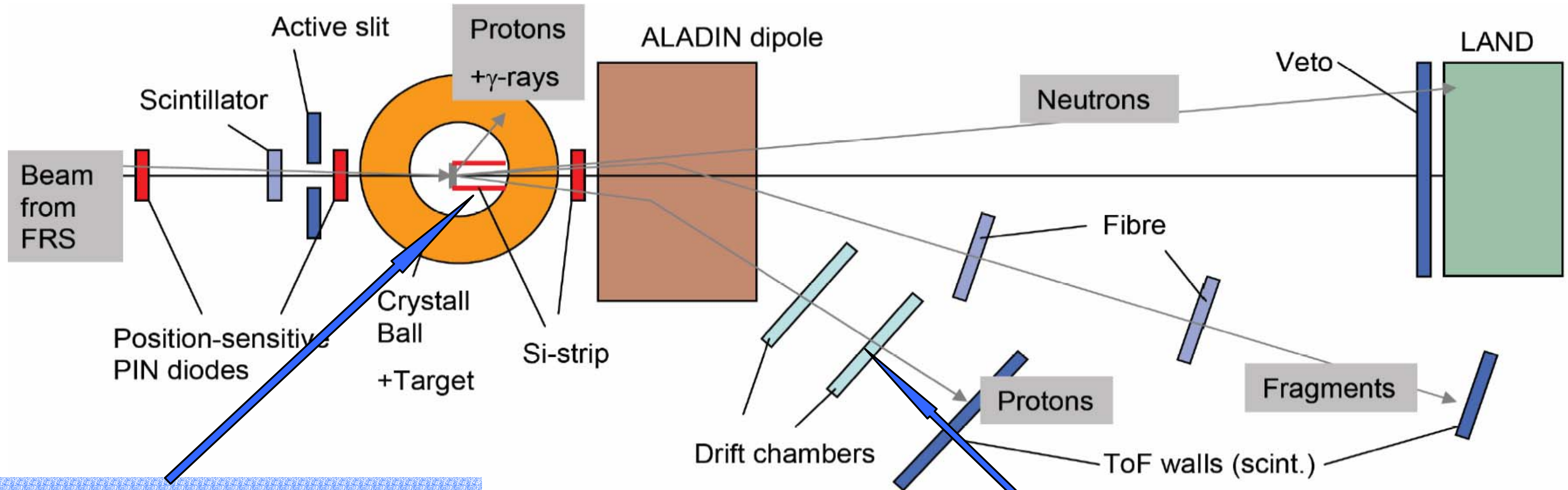


- Correlation density of the ^{17}Ne g.s. WF
- Two peaks, strong "diproton" peak, similar to ^{6}He due to mixing of s^2 and d^2
- s/d configuration mixing is about 50%

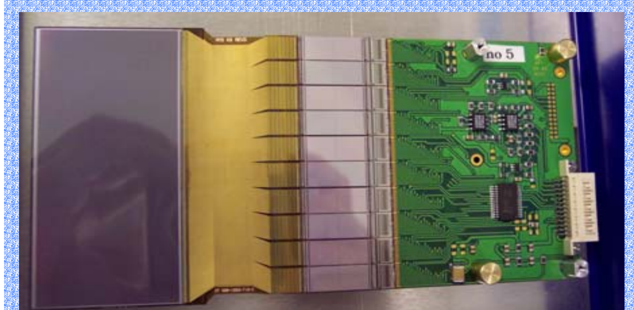
Momentum distributions



Extended experimental Setup at Cave C: Proton detection



new:
proton tracking around the target with Si-strip detectors



detectors ready, first experiment performed at FRS (very good performance)

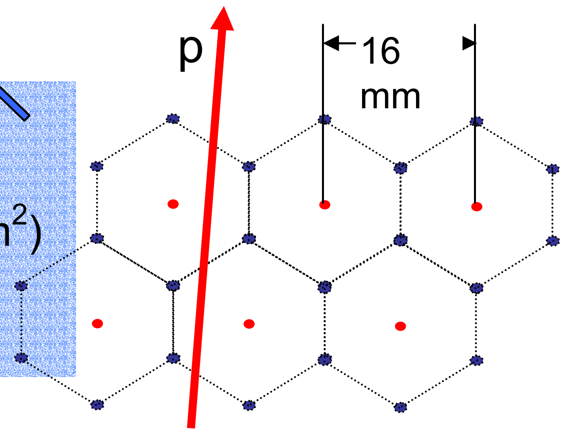
41 × 72 mm², strip pitch 100 μm

Dynamic range – 100 keV - 14 MeV

→ **Prototype for R3B recoil detector**

new:
proton tracking behind magnet with drift chambers (100×80 cm^2)

resolution ~200 μm
operational in 2007



Exclusive measurement of

- inelastic excitation plus neutron and proton decay

- quasi-free scattering: (p,2p), (p,pn)

The LAND/FRS Collaboration S188/S233

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