Shell structure far off stability studied via high-energy reactions

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Evolution of the nuclear shell structure ($6 \leq Z \leq 13$) and recent experimental studies of direct reactions in inverse kinematics at in-flight RIB facilities

- one-neutron removal reactions (nuclear and e.m.)

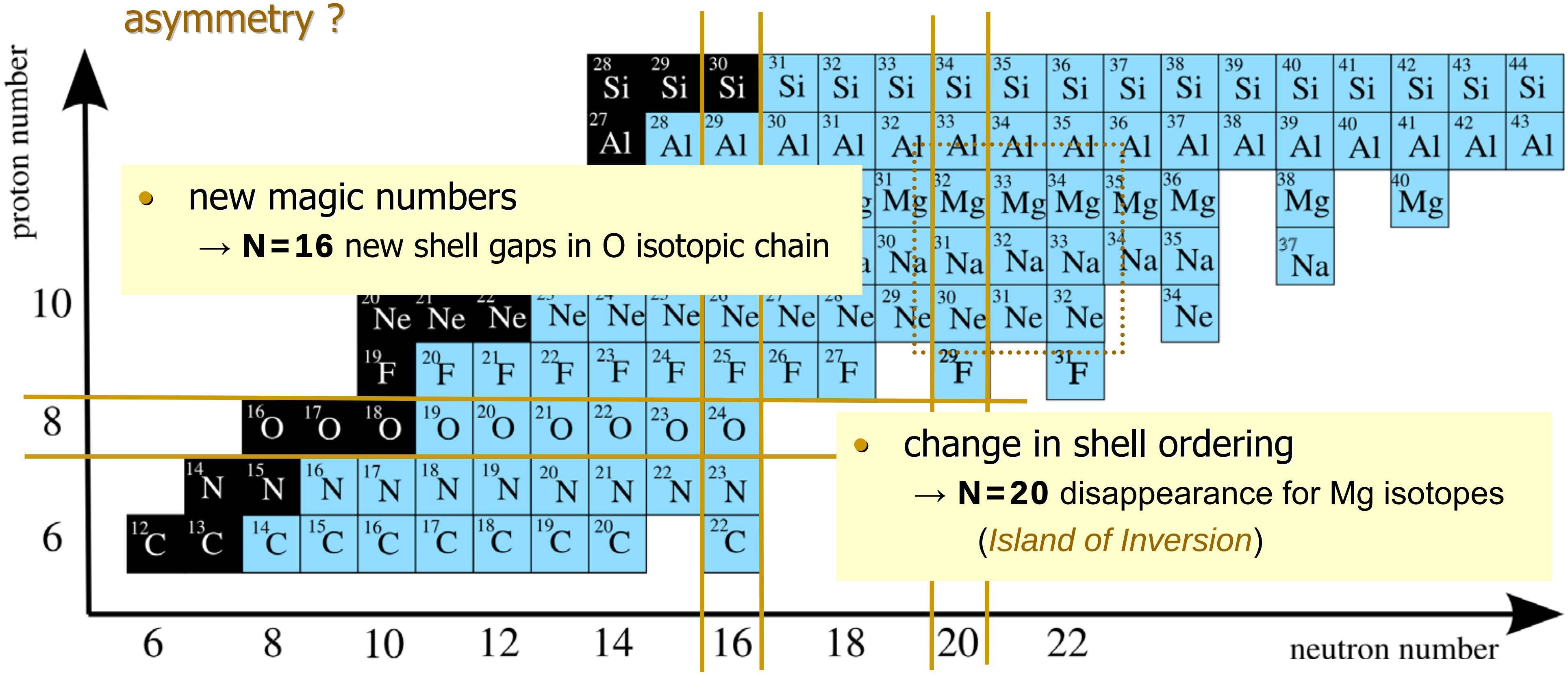
Effects of weak binding

- interaction cross sections
- charge-changing cross sections

"EURORIB´12" May 20-25, 2012 – Abano Terme (Padova), Italy

Magic numbers and shell gaps

To what extent the shell model is still valid in nuclei with large proton-neutron asymmetry ?



- new magic numbers
  → **N=16** new shell gaps in O isotopic chain

- change in shell ordering
  → **N=20** disappearance for Mg isotopes
  (*Island of Inversion*)

- unusual combination of large isospin and weak binding energy
  → large diffuseness of nuclear surface (*halo*) , skin = $\tilde{r}_n - \tilde{r}_p$

In addition, coupling to the continuum is important for pairing, deformations and threshold strength functions.

Drip-line studies in O isotopes

The neutron drip line is reached for Z=8

- Non existence of bound doubly magic nucleus ^{28}O, as well as ^{26}O
  H. Sakurai *et al.* PLB 448 (1990) 180
  D. Guillemaud-Mueller *et al.* PRC 41 (1990) 937
  A. Schiller *et al.* PRC 72 (2005) 037601

- Deduced effective matter density in O nuclei
  A. Ozawa *et al.* NPA 691 (2001) 599

- Non existence of bound excited states in ^{23,24}O
  M. Stanoiu *et al.* PRC 69 (2004) 034312

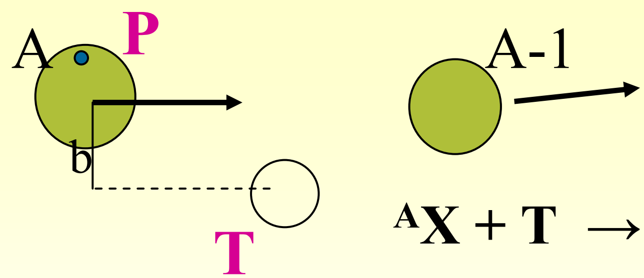
- Measurement of *l=2* resonance in ^{25}O
  C.R. Hoffman *et al.* PRL 100 (2008) 152502

  gap *s1/2–d3/2* : 4.86(13) MeV

Presence of a spherical shell closure ⟶ measuring the **neutron occupancy**

1n removal reactions

At high energy



$^{A}X + T \rightarrow {}^{A-1}X + (\gamma)$

structure & reaction mechanism can be much easily disentangle

calculations: Glauber model (eikonal approx.) $|\psi>$ = core $\otimes$ neutron,

distorsion due to core survival

$$\frac{d\sigma}{dp_{//}} = \int d\mathbf{r_t} \left| \frac{1}{\sqrt{2\pi}} \int \varphi_0(\mathbf{r_t}, z) e^{ip_z z} \right|^2 \int d\mathbf{b} D(\mathbf{b}, \mathbf{r_t})$$

Sensitivity of the p// distribution to single particle states:

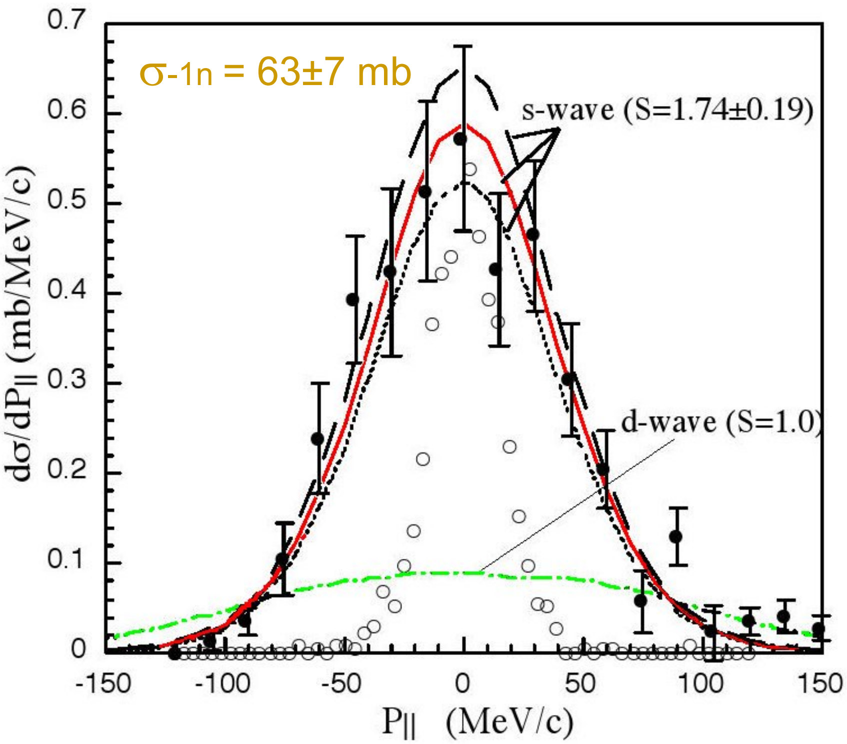
- Shape of $d\sigma/dp_{//}$ of the residual nucleus $\longrightarrow$ l_n of the removed nucleon
- Cross section σ_{-1n} $\longrightarrow$ spectroscopic factors

Pioneered at GANIL, GSI, MSU and RIKEN

N =16 magic number and shell gap

^{24}O: 1*n* removal reaction @920 MeV/u

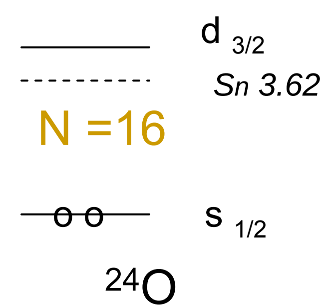
In the c.m. frame: $P_{||} = \gamma_b (P_f^{lab} - \beta_b E_f^{lab})$



^{23}O states

Spin	SDPF-M Energy(MeV)	SDPF-M C^2S	USDB Energy(MeV)	USDB C^2S	Exp S
$1/2^+$	0.0	1.769	0.0	1.810	1.74(19)
$5/2^+$	2.586	5.593	2.593	5.665	
$3/2^+$	4.736	0.065	4.001	0.090	

... in agreement with shell model calculations

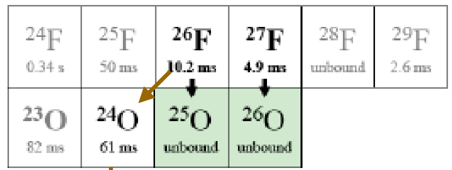


s-wave dominance indicates the presence of a new shell closure at N=16 in ^{24}O

R. Kanungo *et al.*, PRL 102 (2009) 152501

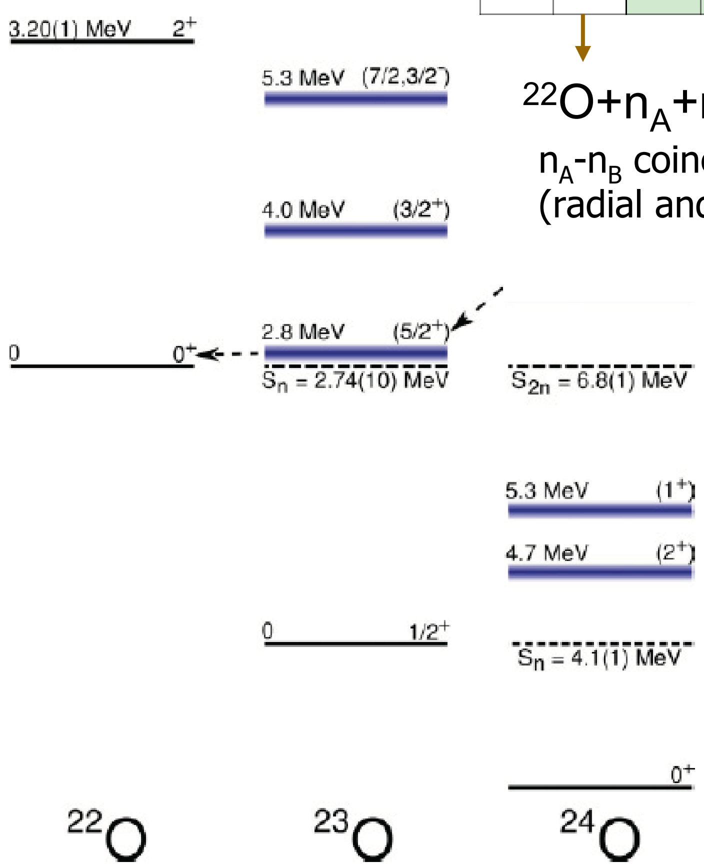
^{24}O resonance above S_{2n}

Experimental levels

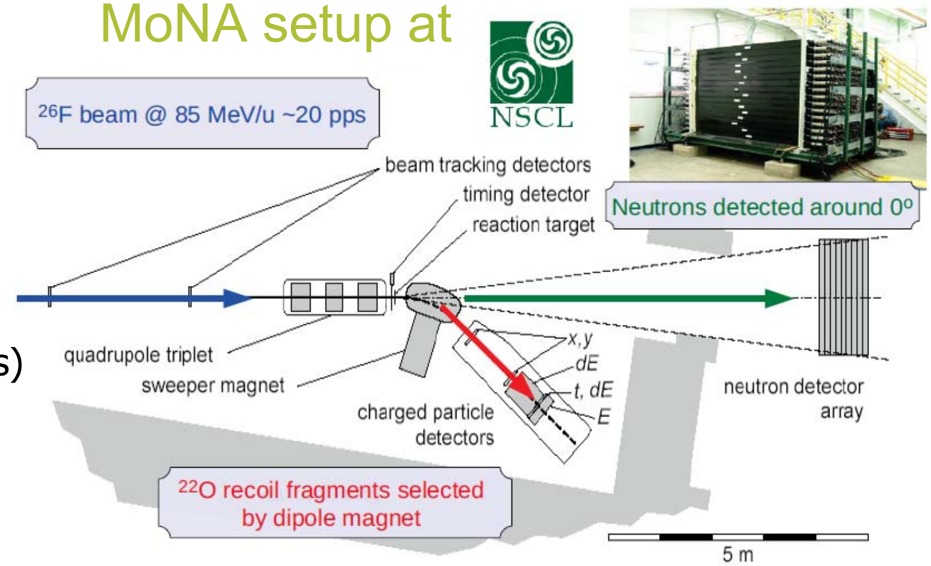


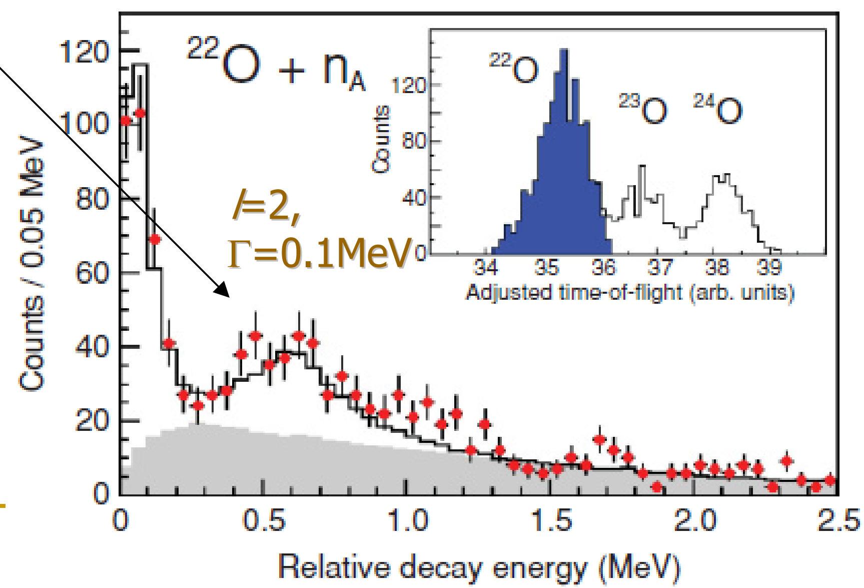
^{22}O+n_A+n_B

n_A-n_B coincidences
(radial and velocity cuts)



MoNA setup at

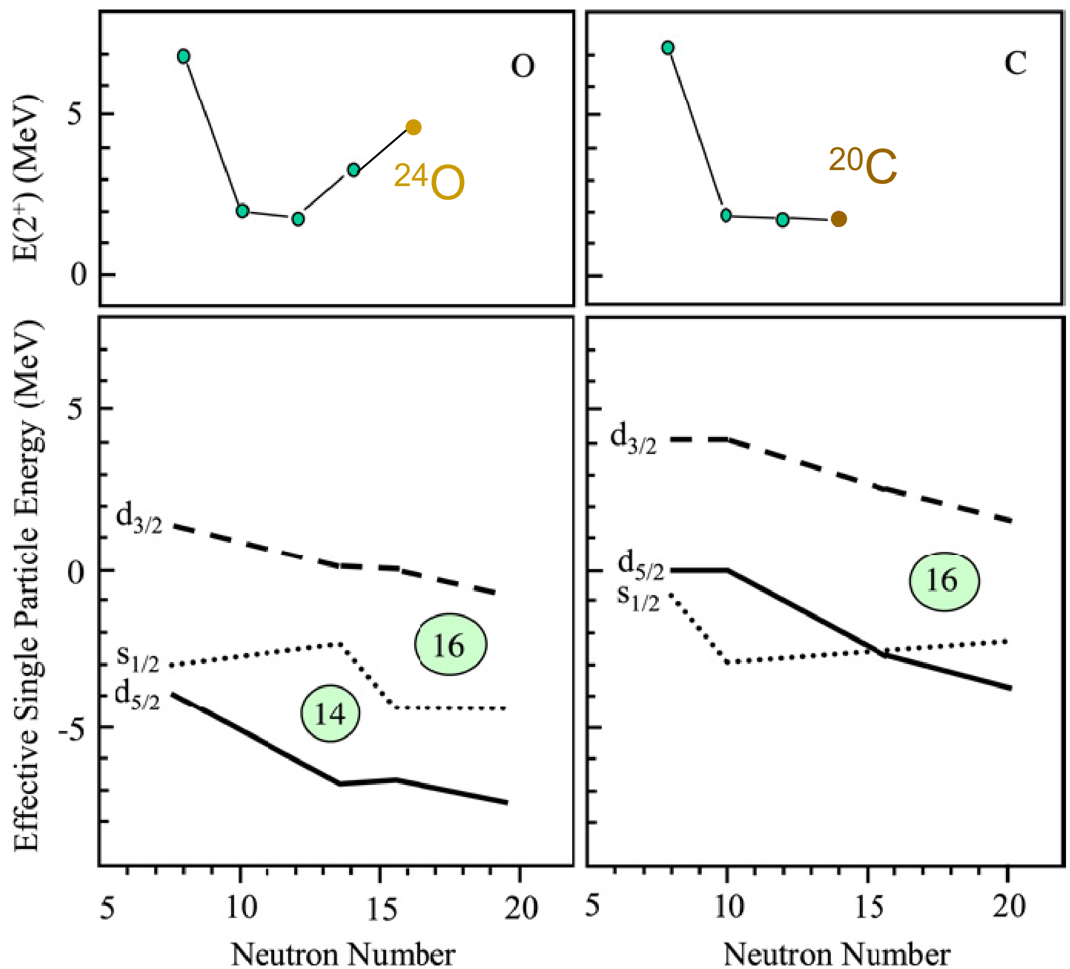




C.R. Hoffman *et al.*, PRC 83 (2011) 031303(R)

Comparison between O and C systematics

O. Sorlin, M.-G. Porquet / Progress in Particle and Nuclear Physics 61 (2008) 602–673



$E(2^+)$ = 4. 7 MeV

C.R. Hoffman *et al.* PLB 672 (2009) 17

B(E2) = 7.5 e^2fm^4, increases at N=14

M. Petri *et al.* PRL 107 (2011) 102501

- N=14 gap does not exist, $d_{5/2}$ starts to be filled in ^{16}C
- N=16 gap predicted in ^{22}C, candidate as doubly magic nucleus

The drip-line nucleus ^{22}C

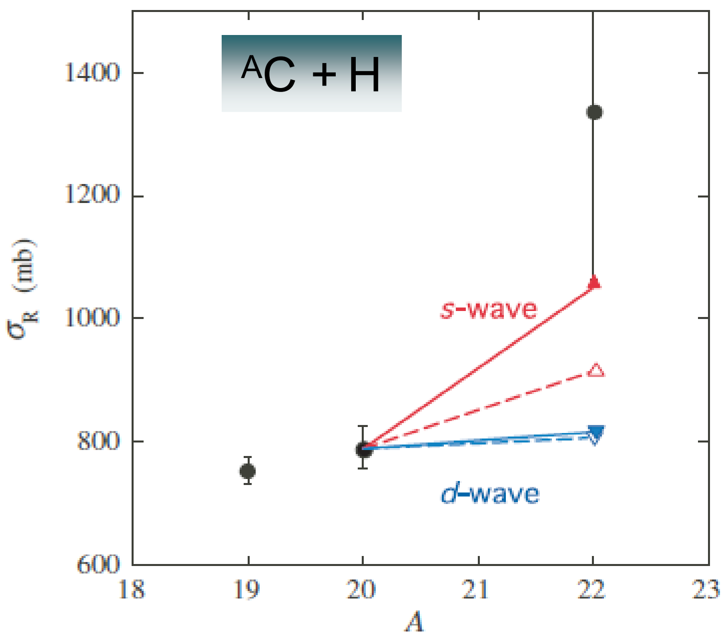
$\sigma_R = \sigma_I + \sigma_{inel}$

if the nucleus has no excited bound states

$\sigma_{inel} \sim 0 \longrightarrow \sigma_I \approx \sigma_R$

Transparency

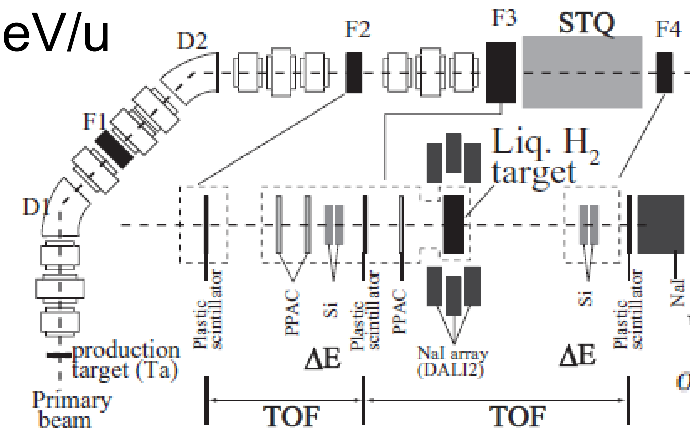
$$\sigma_R = 2\pi \int_0^\infty [1 - T(b)]\, b\, db$$



K. Tanaka *et al.*, PRL 104 (2010) 062701

E ~40 MeV/u

TOMBEE setup at RiPS (RIKEN)



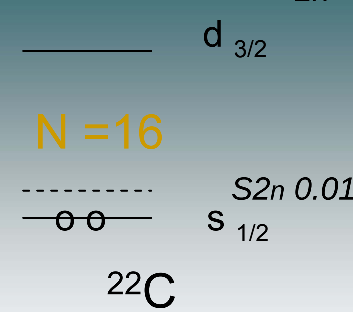
~10 ^{22}C/h

$$\sigma_I = \frac{1}{t}\ln\left(\frac{R_o}{R_i}\right)$$

^{40}Ar I=100pnA @63MeV/u

S_{2n}^{exp} = 420 ± 940 keV

- pure s^2 with lower S_{2n}



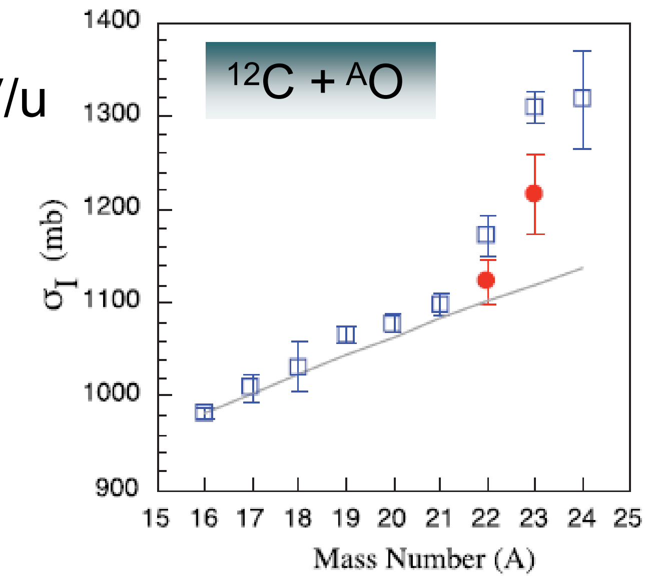
- s-wave dominance with core perturbation

O systematics

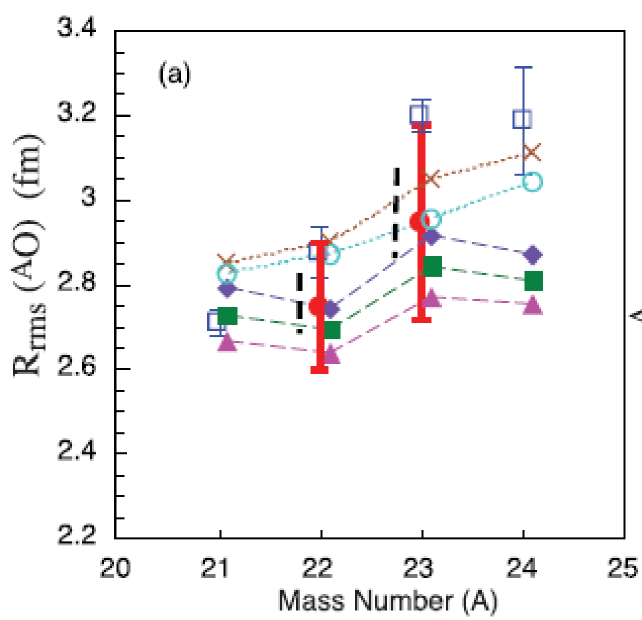
- new GSI data (Kanungo *et al. 2011*)
- □ previous GSI data (Ozawa *et al. 2001*)

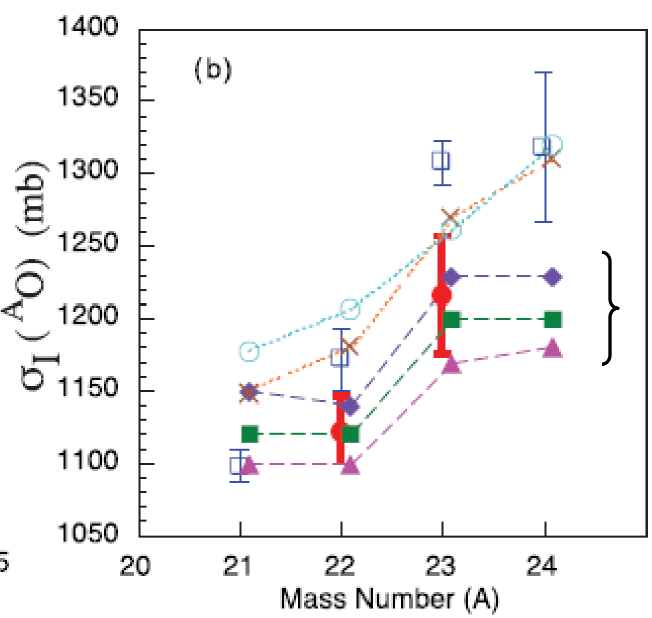
Anomaly: 12% difference between $\sigma_I(^{22}O)$ and $\sigma_I(^{23}O)$, not consistent with ^{22}O inert core+n

E ~900 MeV/u



Isotope	$\sigma_I(\Delta\sigma)$ (mb)	$\Delta\sigma$(Stat.) (mb)	$\Delta\sigma$(Syst.) (mb)	$R_{rms}^{m(Fermi)}$ (fm)	$R_{rms}^{m(HO)}$ (fm)
^{22}O	1123(24)	18.5	15.3	2.75(0.15)	2.75(0.07)
^{23}O	1216(41)	33.1	24.7	2.95(0.23)	2.97(0.11)



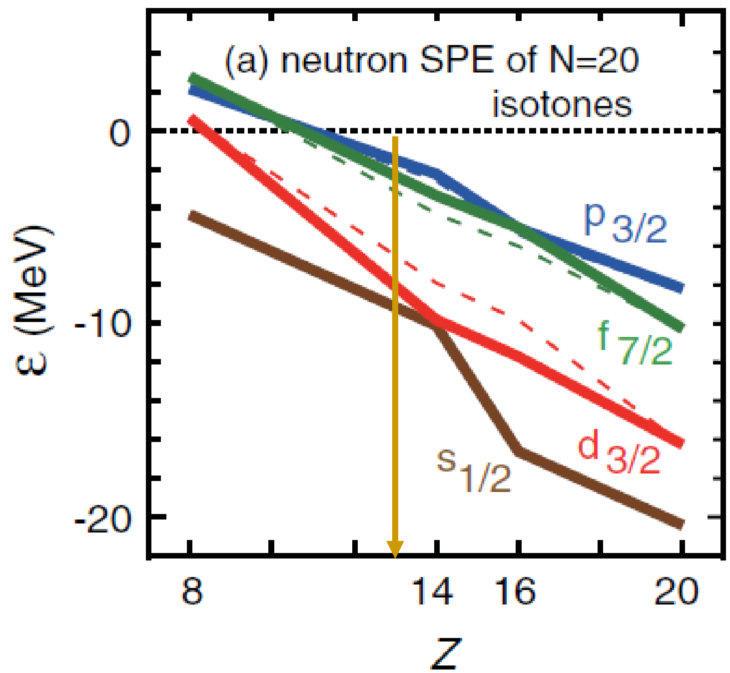


X Skyrme-HF (Y.Suzuki *et al.*)

O RMF (B.A.Brown *et al.*)

coupled-cluster calc. (G. Hagen *et al.*)

N=20 gap evolution



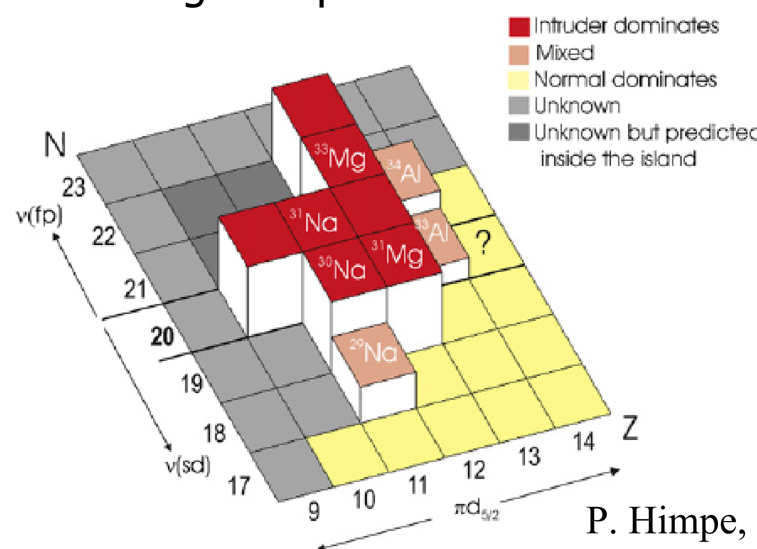
Z=8 → Z=20 , adding *sd* protons

→ wide N=20 gap

T. Otsuka *et al.*, PRL 104 (2010) 012501

Direct measurements of the weakness of the N=20 shell closure are difficult at lower Z

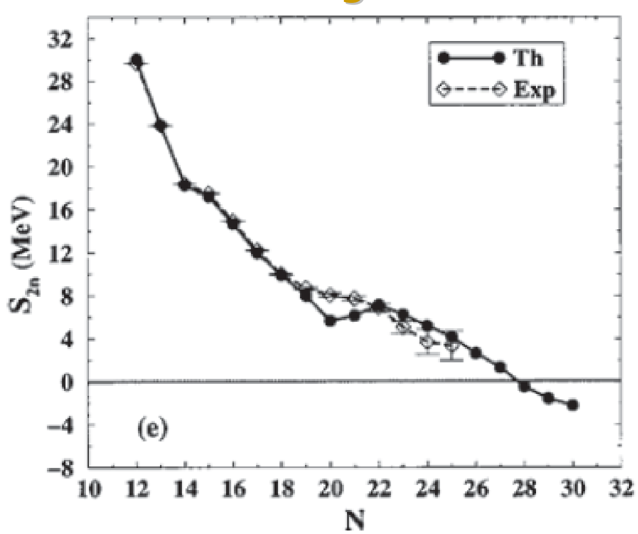
The n-rich Al isotopes are easier to access experimentally and are located in a *transition* region between the spherical shell of Si nuclei and the deformed Mg isotopes.



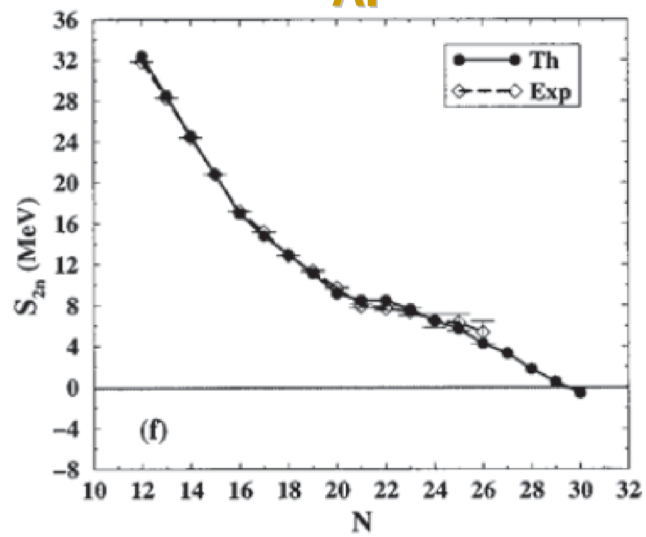
P. Himpe, *et al.*, PLB 658 (2008) 203

Two-neutron separation energy S_{2n}

Mg



Al



E. Caurier, *et al.*, PRC 58 (1998) 2033

Al: Exp S_{2n} do not show anomalies and are perfectly reproduced by shell model calculations involving the full *sd* proton shell (Z=8) and the *pf* neutron shell (N=20) as valence space

Al isotopic chain (A=32-36)

- β-decay and g-factor measurements available up to A=34

magnetic moments measurements of ^{33,34}Al performed at GANIL show large discrepancies with shell model predictions

→ non-negligible presence of intruder configurations

~ 25% in ^{33}Al and 60% in ^{34}Al, at least

(P. Himpe, *et al.*, PLB643 (2006) 257 , PLB658 (2008) 203)

→ polarization effects due in even-mass Al (N=21-23) to the unpaired $1d_{5/2}$ proton

pf shell

N =20

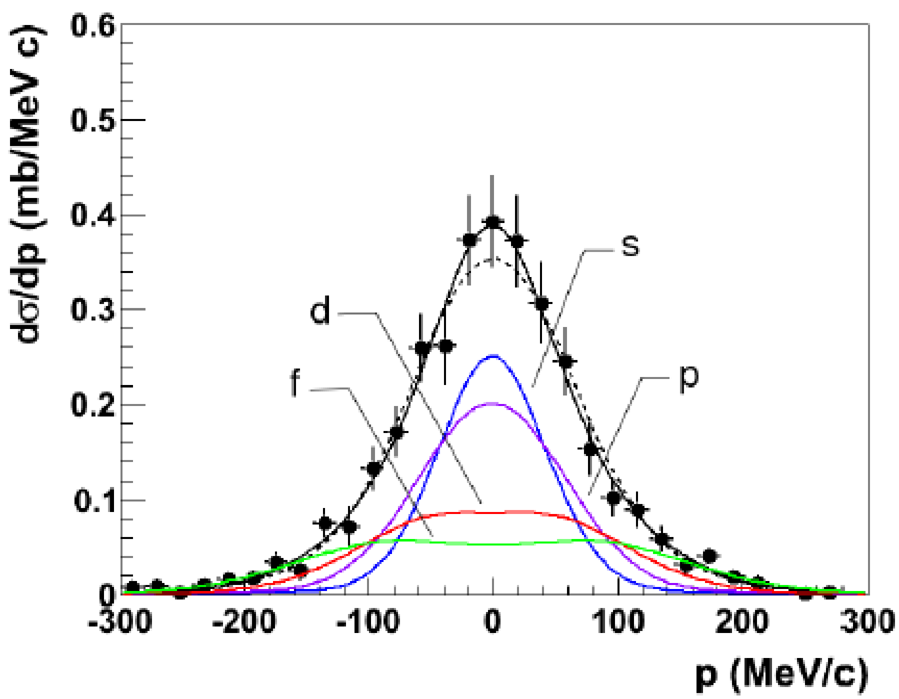
$1d_{5/2}$ ~~ooooox~~ *sd shell*

p n

1n removal reactions test the neutron single particle structure

^{33}Al → n + ^{32}Al at 922 MeV/u

σ_{-1n}= 64±3 mb, Γ_{FWHM}= 136±3 MeV/c



$^{33}Al_{g.s.}$(5/2$^+$): shell model calc. (USDB)

C^{2}S = 1.40 (ℓ=0) ← ***15-40% higher***

C^{2}S = 3.61 (ℓ=2)

pf shell S_n=5.54 MeV

N =20

$1d_{5/2}$ oooooox *sd shell*

p n

Adding ℓ=1, 3 (p- and f-waves) } with negative parity core state (E(4$^-$)=1.2 MeV)

does not change the results of the fit

— **fit**

S(ℓ=0) = $0.93^{+0.28}_{-0.13}$ **s-wave**

S(ℓ=2) = $1.46^{+0.27}_{-0.15}$ **d-wave**

--- fit assuming S(ℓ=0) = 0

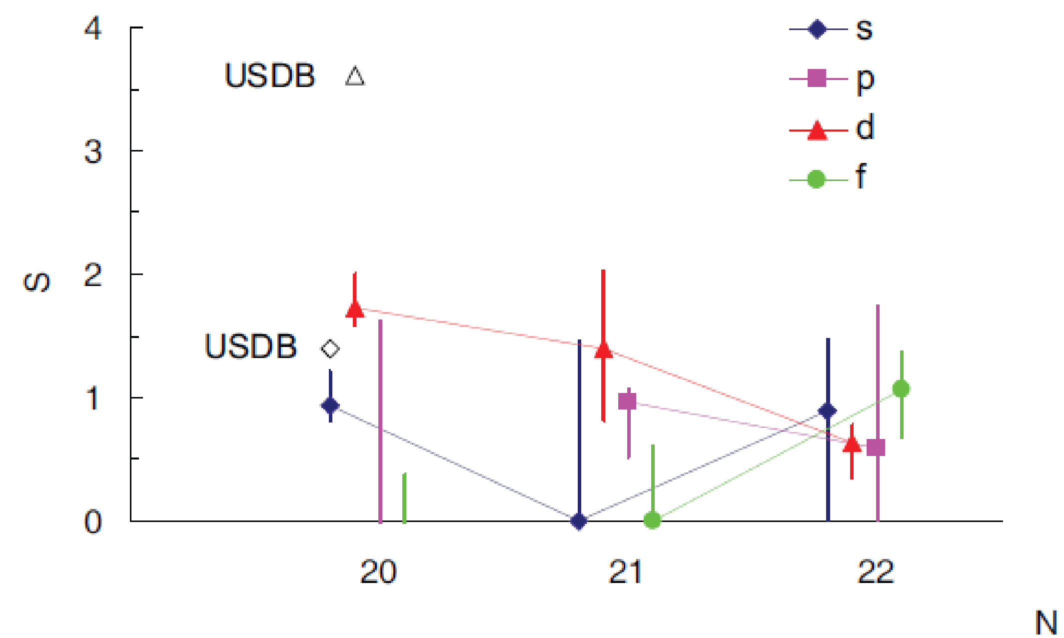
S(ℓ=1) < 1.63, 60% upper limit

intruder configurations

Mixing in $^{33\text{-}35}Al_{g.s.}$

$$\sigma_{-1n} = \sum_l S_l \, \sigma^{sp}(\, \psi_{nlj} \otimes Al\,(I_c^\pi)\,)$$

Evolution of single particle neutron occupancy



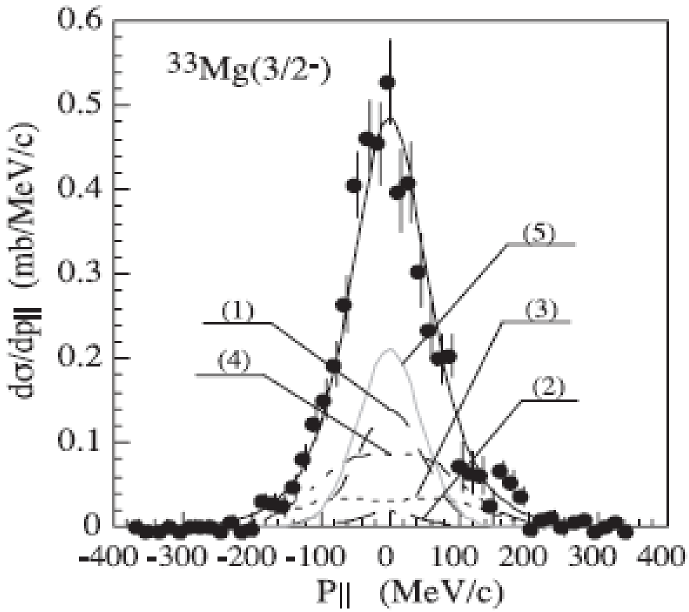
^{33}Al ^{34}Al ^{35}Al

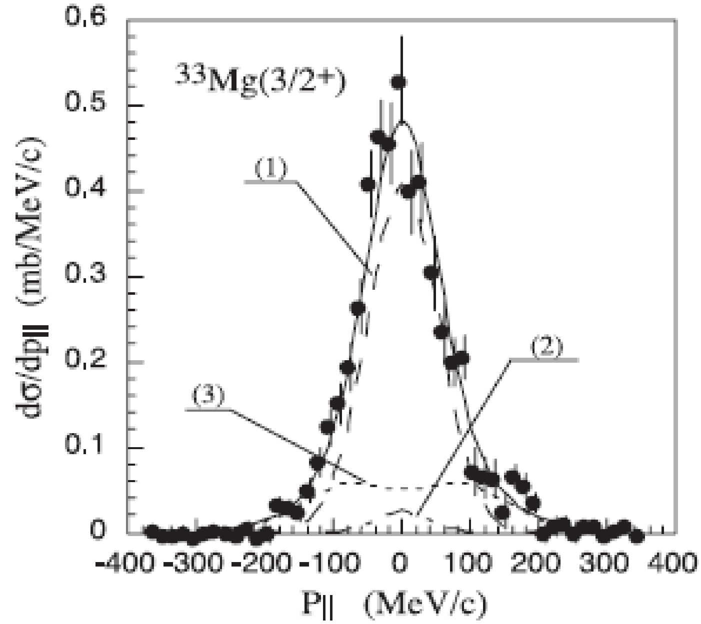
Increasing *pf* occupancy

C. Nociforo *et al*., PRC 85 (2012) 044312

Lowering of $2p_{3/2}$ in ^{33}Mg

From the momentum analysis $J^{\pi}=3/2^{+}$ cannot be excluded





The shape of the p// distribution is much narrower than predictions, suggesting a larger occupancy of neutrons in the $2p_{3/2}$ orbital

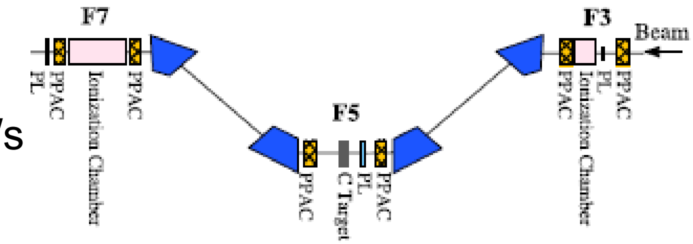
R. Kanungo *et al*., PLB 685 (2010) 253

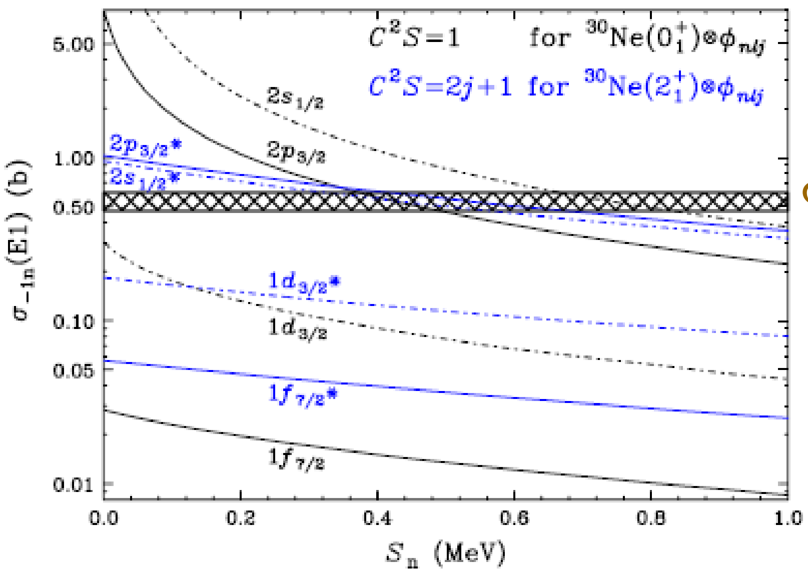
The halo candidate ^{31}Ne

(MS)BigRiPS at RIKEN

^{31}Ne +Pb → ^{30}Ne + n @230 MeV/u

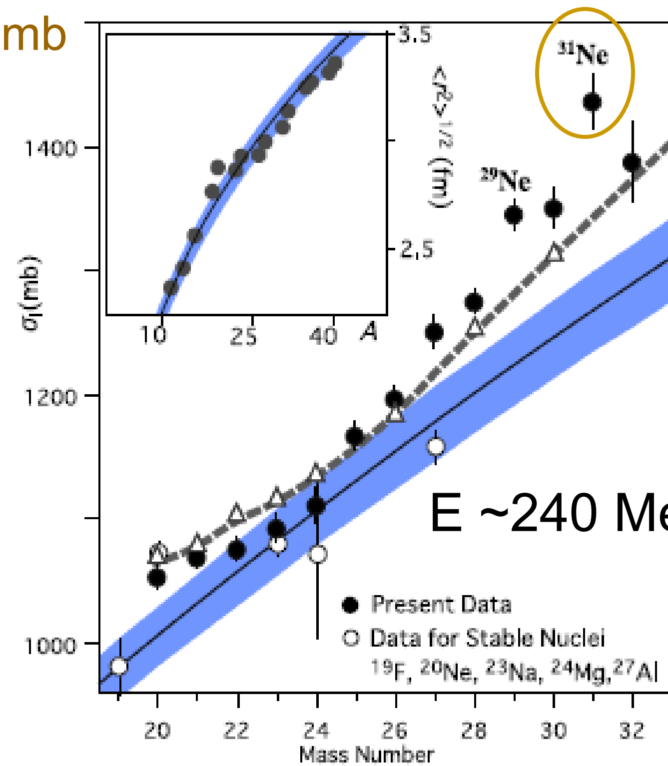
~5 ^{31}Ne/s





σ ^{exp} = 540(70)mb

^{A}Ne + ^{12}C



E ~240 MeV/u

From Coulomb breakup and reaction cross section

→ low *l* configuration with weak binding energy

(S_n^{exp} = 0.29±1.64 MeV)

in agreement with halo formation

Shell model predicts J$^{\pi}$ (^{31}Ne$_{g.s.}$)= 3/2^{-}

T. Nakamura *et al.*, PRL 103 (2009) 262501

M. Takechi *et al.*, PLB 707 (2012) 357

Direct breakup model

After projection on *core* states $\mathbf{I}_c^\pi$, identified by means of *γ-ray coincidences* :

E1 matrix element

$N_{E1}(E^*)$ calcultated in semiclassical approx.

$$\frac{d\sigma}{dE^*}(I_c^\pi) = \frac{16\pi^3}{9\hbar c} N_{E1}(E^*) \sum_{nlj} C^2 S(I_c^\pi, nlj) \sum_m \left| \left\langle \mathbf{q} \left| \frac{Ze}{A} r Y_m^1 \right| \psi_{nlj}(\mathbf{r}) \right\rangle \right|^2$$

spectroscopic factor

The differential cross section for e. m. excitations provides information on the quantum numbers and spectroscopic factors of ground state configuration

Advantages

- interaction is well known
- high energy approximation
- sensitivity to low *l* values

Limitations

- core excited states to be identified
- only for weakly bound breakup systems

Pioneered at RIKEN and GSI

Mg systematics

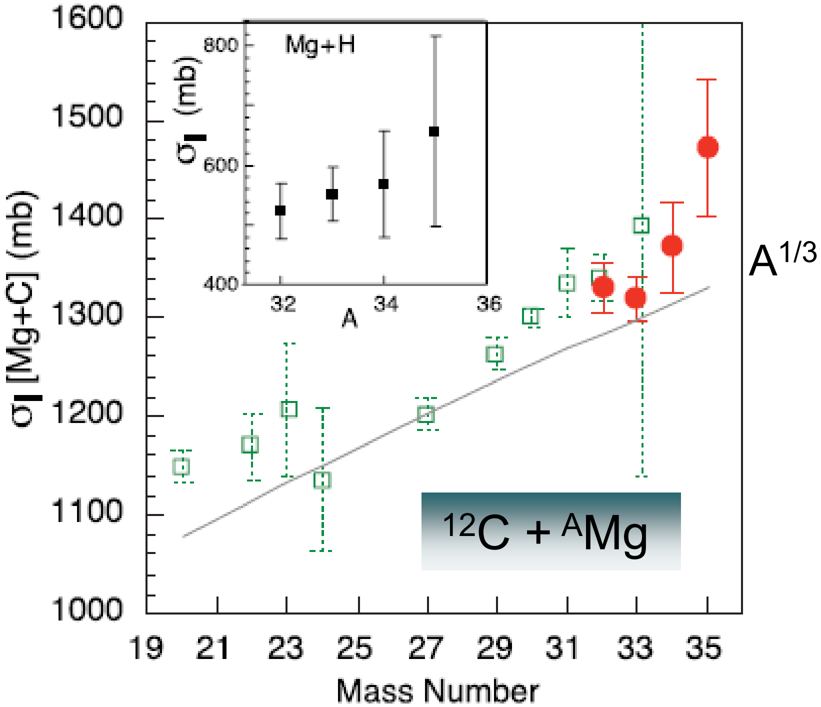
^{32}Mg : $\tilde{r}_n - \tilde{r}_p$ ~ 0.13 fm

Isotope	σ_I^C (mb)	σ_I^H (mb)	R_{rms}^m (ex) (fm)	HF [6][a] (fm)	RMF [20] (fm)
^{32}Mg	1331(24)	523(47)	3.17 ± 0.11	3.20	3.21
^{33}Mg	1320(23)	552(45)	3.19 ± 0.03	3.23	3.26
^{34}Mg	1372(46)	568(90)	3.23 ± 0.13	3.26	3.33
^{35}Mg	1472(70)	657(160)	3.40 ± 0.24	3.30	3.38

Few-body Glauber model

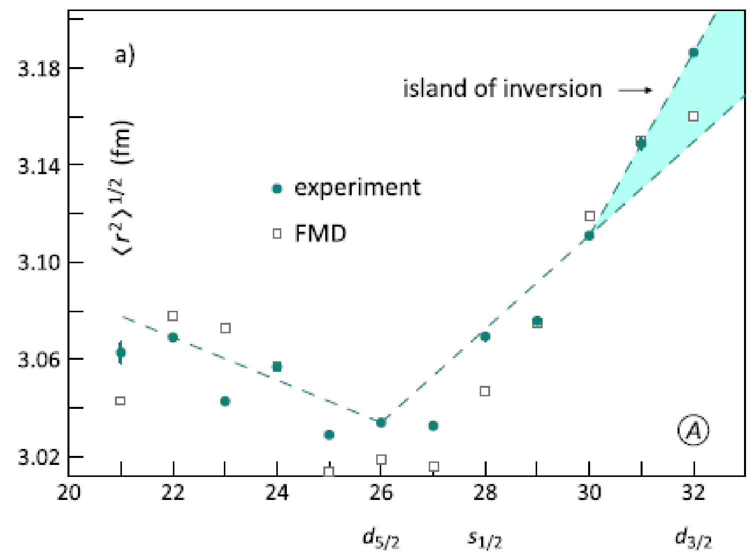
(optical limit + high order terms)

E ~900 MeV/u



- new GSI data (Kanungo *et al.* 2011)
- □ previous GSI data (Suzuki *et al.* 1998)

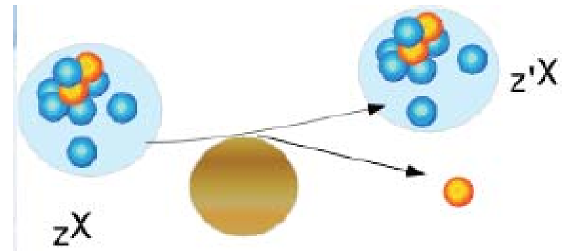
^{32}Mg : R_c = 3.1863(161) fm



- odd-even staggering
- correlation with the n configuration

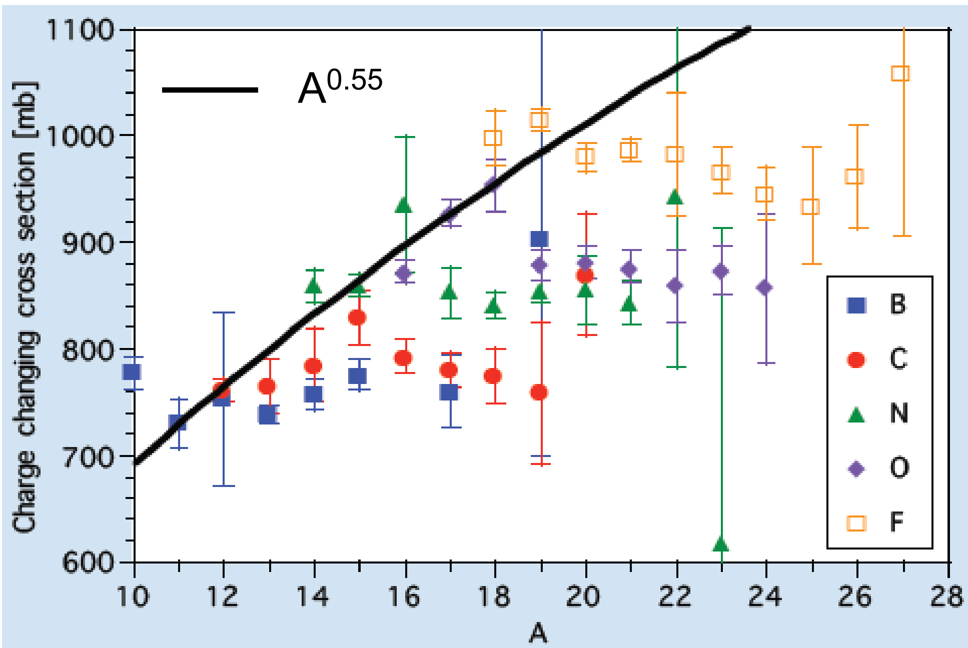
D.T. Yordanov *et al.*, PRL 108 (2012) 042504

GSI σ_{CC} data



σ_{cc} increases with Z but not with N

$$\sigma_{cc} = \frac{1}{t}\ln\left[\frac{\left(\frac{N_{sameZ}}{N_{in}}\right)_{Tout}}{\left(\frac{N_{sameZ}}{N_{in}}\right)_{Tin}}\right]$$



L.V. Chulkov *et al.*, NPA 674 (2000) 330

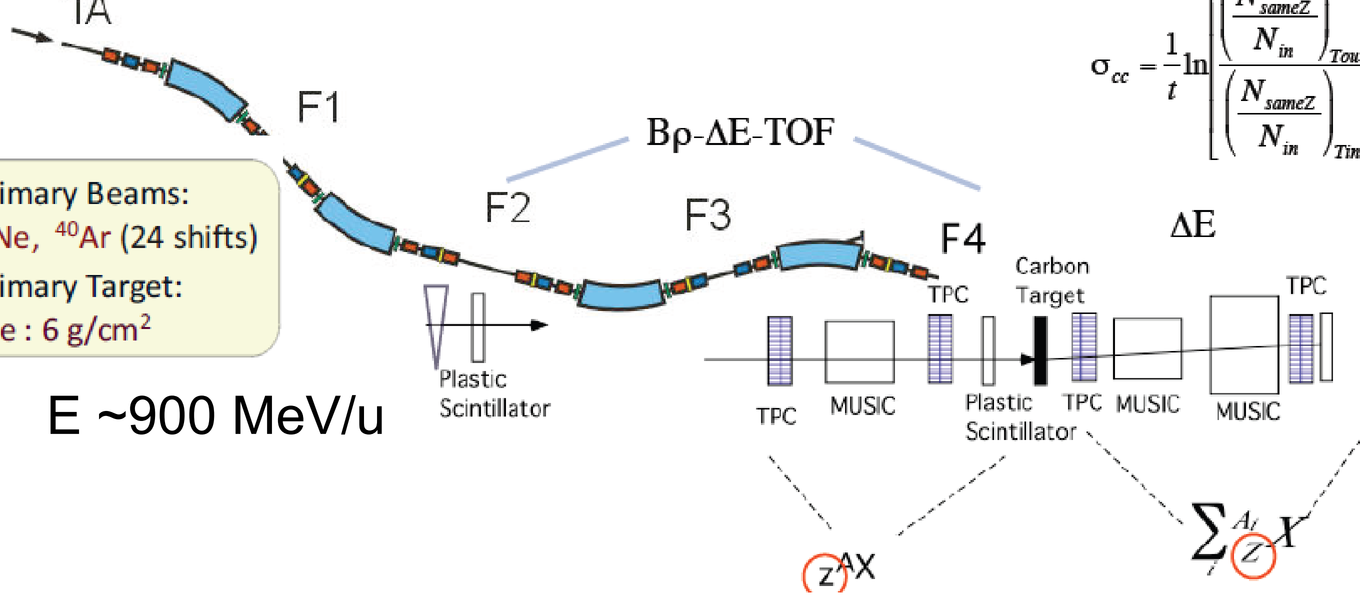
Accurate measurements of σ_{cc} can provide information on

- *neutron skin* in light exotic nuclei
  - σ_I ⟶ matter radii
  - σ_{CC} ⟶ charge radii

Measurements for some stable nuclei are not consistent with Berkeley data

W.R.Webber *et al.*,PRC 41(1990) 520

Experimental technique



$$\sigma_{cc} = \frac{1}{t}\ln\left[\frac{\left(\frac{N_{sameZ}}{N_{in}}\right)_{Tout}}{\left(\frac{N_{sameZ}}{N_{in}}\right)_{Tin}}\right]$$

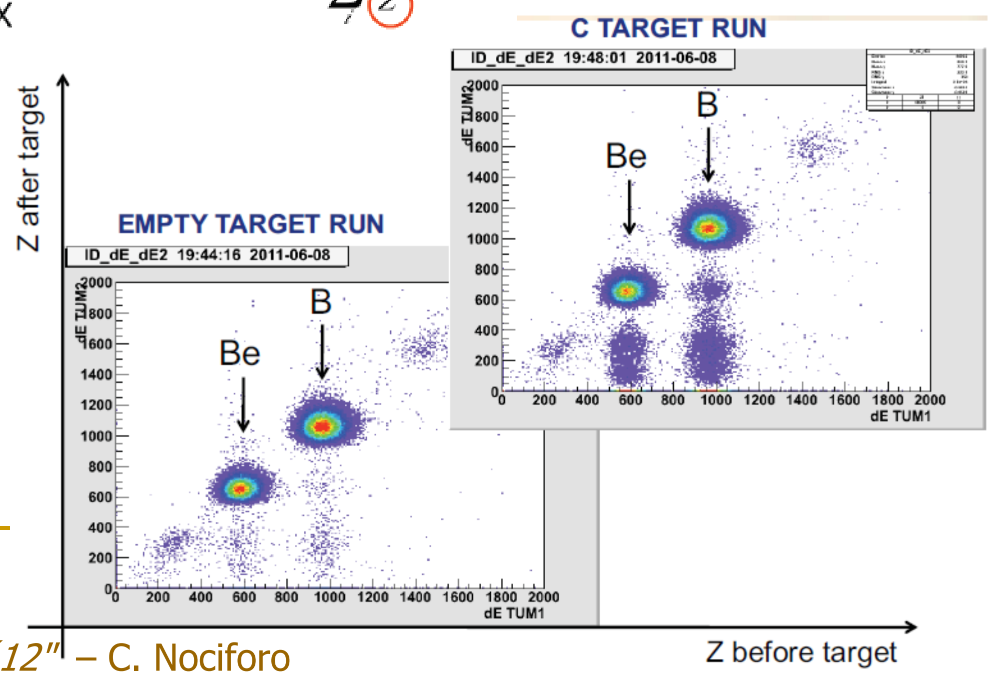
Primary Beams:
^{22}Ne, ^{40}Ar (24 shifts)
Primary Target:
^{9}Be : 6 g/cm^2

E ~900 MeV/u

Fragments:
B, **C**, **O** (Be, N)
isotopic chains

Complementary to:

- isotope-shift experiments
- electron scattering



Experiment performed in 2011, data analysis is in progress

Summary

Recent experimental studies performed by using *standard* tools (σ_{-1n} , $p_{//}$, $\sigma_{e.m.}$, σ_I , σ_{cc}) to understand the structure of weakly bound neutron-rich light nuclei:

- N = 16 spherical shell closure
  - ^{24}O studies at GSI and MSU, new doubly magic nucleus
  - ^{22}C studies at RIKEN, s-wave dominance

  O systematics → σ_I value consistent with $|^{23}O_{g.s.}\rangle = |^{22}O(0^+) \otimes s_{1/2}\rangle$

- N = 20 gap quenching
  - $^{33-35}$Al, ^{33}Mg studies at GANIL and GSI, lowering of $2p_{3/2}$

  Mg systematics → mattter and charge radii, moderate skin in ^{32}Mg

  - ^{31}Ne studies at RIKEN, s- or p-wave dominance

  Ne systematics → ^{29,31}Ne halo candidates

Opportunities for research with reactions of drip-line nuclei are foreseen at present and future RIBs facilities.

Acknowledgments

T. Aumann[1], D. Boutin[2], B. A. Brown[4], D. Cortina-Gil[5], B. Davids[6], M. Diakaki[7], A. Estrade[1], F. Farinon[1,2], H. Geissel[1], R. Gernhäuser[8], R. Janik[9], B. Jonson[10], R. Kanungo[3], B. Kindler[1], R. Knöbel[1,2], R. Krücken[8], N. Kurz, M. Lantz[10], H. Lenske[2], Yu.A. Litvinov[1], K. Mahata[1], P. Maeirbeck[8], A. Musumarra[11,12], T. Nilsson[10], T. Otsuka[13], C. Perro[3] , A.Prochazka[1,2], C. Scheidenberger[1,2], B. Sitar[9], P. Strmen[9], B. Sun[2], I. Szarka[9], I. Tanihata[14], H. Weick[1], M. Winkler[1]

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