Shell evolution in neutron-rich Al isotopes around N=20 shell closure

Chiara Nociforo
GSI, Darmstadt

- Evolution of neutron shell structure
  → **magic numbers (N =16, 20), shell gaps**
- GSI- FRS results on one-neutron removal reactions
  → **$^{32\text{-}34}$Al momentum distribution analysis**

"DREB12" March 26-29, 2012 – Pisa, Italy

Magic numbers and shell gaps

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

For light nuclei far off stability

- new magic numbers

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

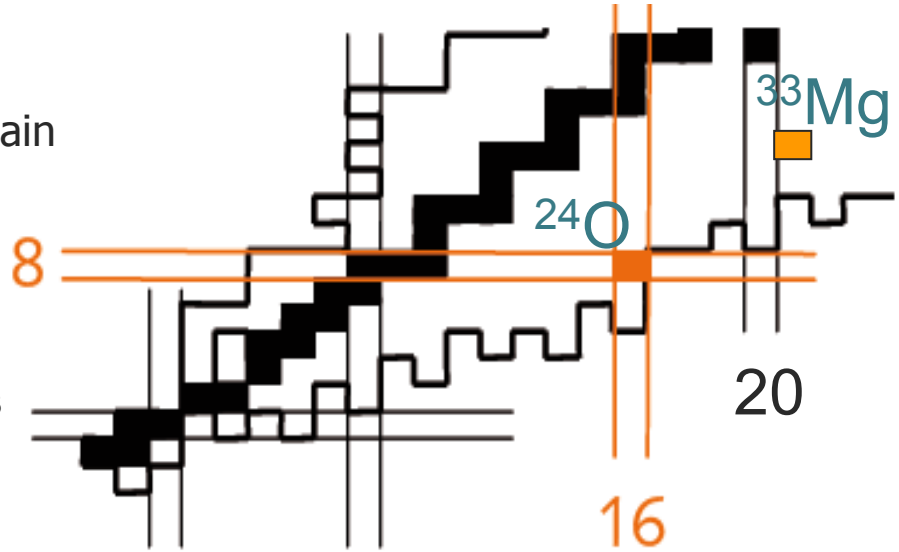
  R. Kanungo, *et al.*, PRL 102 (2009) 152501

- change in shell ordering

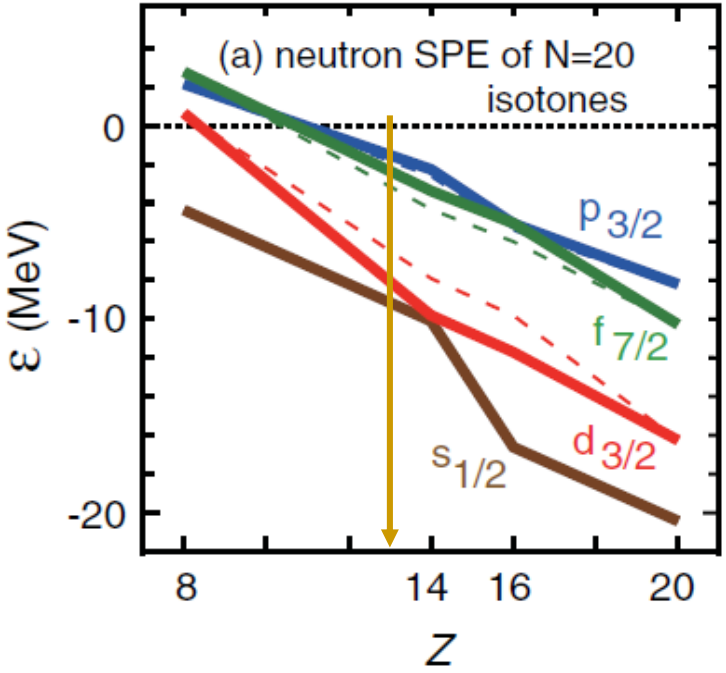
  → **N=20** disappearance for Mg isotopes

  (*Island of Inversion*)

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



N=20 gap evolution



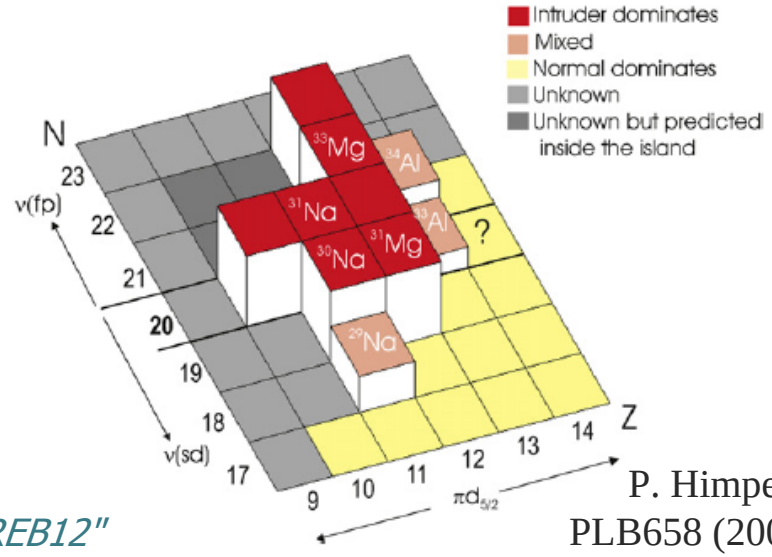
Z=8 → Z=20 , adding *sd* protons

→ wide N=20 gap

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

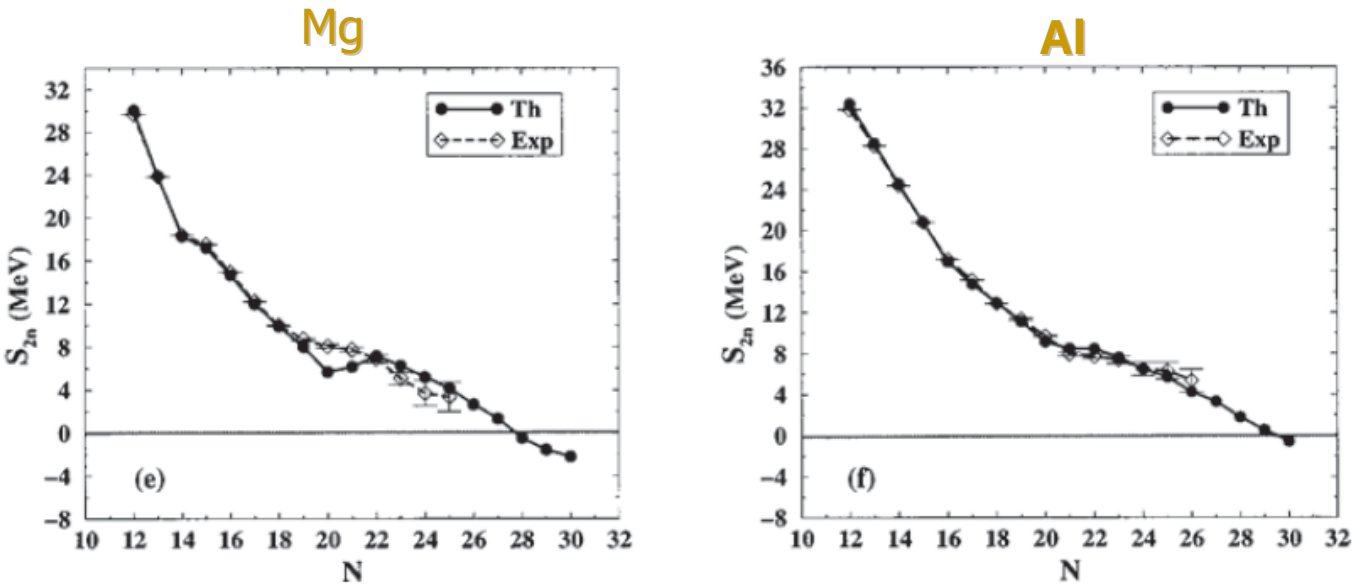
Direct measurements of the weakness of the N=20 shell closure are difficult at lower Z

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.*, PLB658 (2008) 203

Two-neutron separation energy S_{2n}



E. Caurier, *et al.*, PRC58 (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 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

sd shell

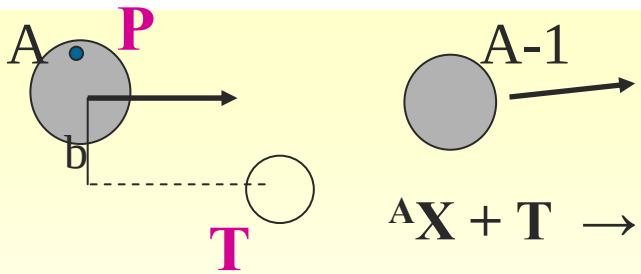
$1d_{5/2}$ ooooox

p n

1n removal reactions test the neutron single particle structure

1n removal reactions at relativistic energies

At high energy



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

structure & reaction mechanism can be much easily disentangle

calculations: Glauber theory $\longrightarrow$ $|\psi>$ = core + neutron, eikonal approx.

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

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

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

C. Nociforo -"DREB12"

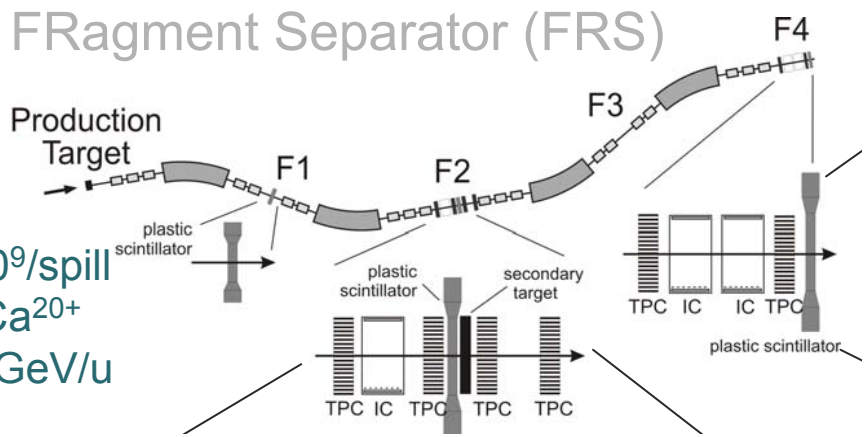
Experimental technique

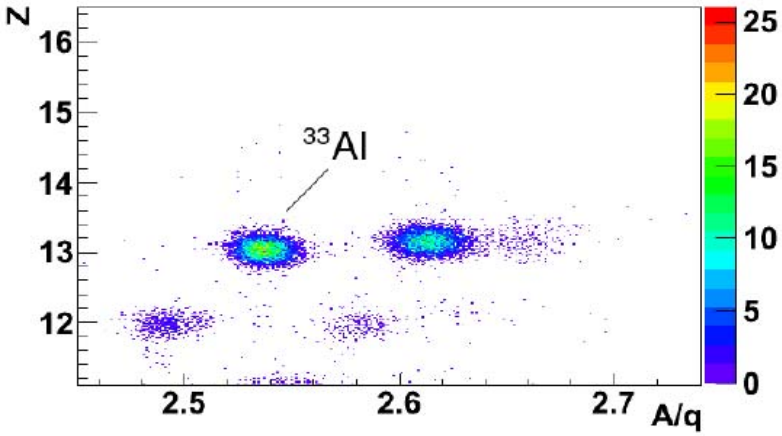
Relativistic energy RIBs advantages:

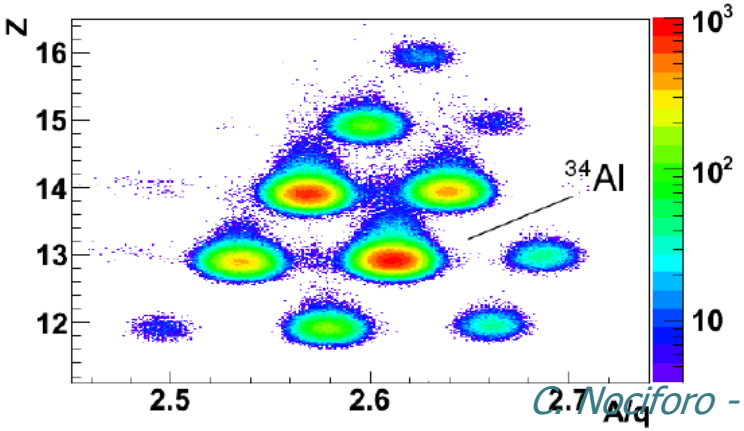
- thick target
- small forward scattering angles

FRagment Separator (FRS)

2 10^9/spill
$^{48}Ca^{20+}$
@1GeV/u





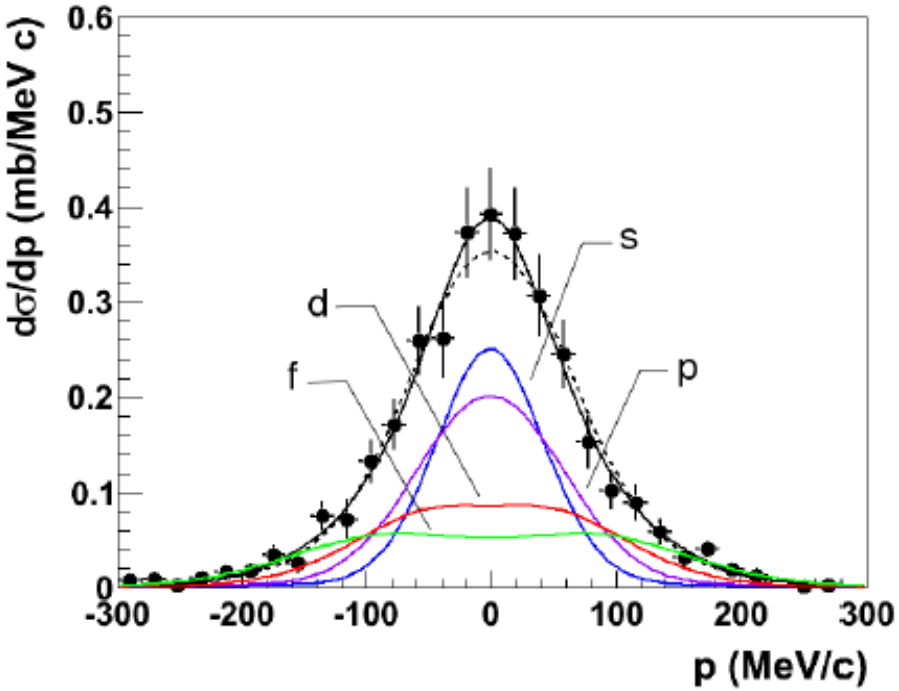


High-resolution momentum ($\Delta p/p \sim 1.5 \cdot 10^{-4}$) in 1n removal channel

$$p_{lab} = B\rho \cdot q \cdot \left(1 + \frac{x_{F4} - C \cdot x_{F2}}{D_{F2-F4}}\right)$$

$^{33}Al \rightarrow n + ^{32}Al$ 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^2S = 1.40 (*l*=0) ← ***15-40 % higher***

C^2S = 3.61 (*l*=2)

pf shell S_n=5.54 MeV

N =20

1d$_{5/2}$ ~~ooooox~~ *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

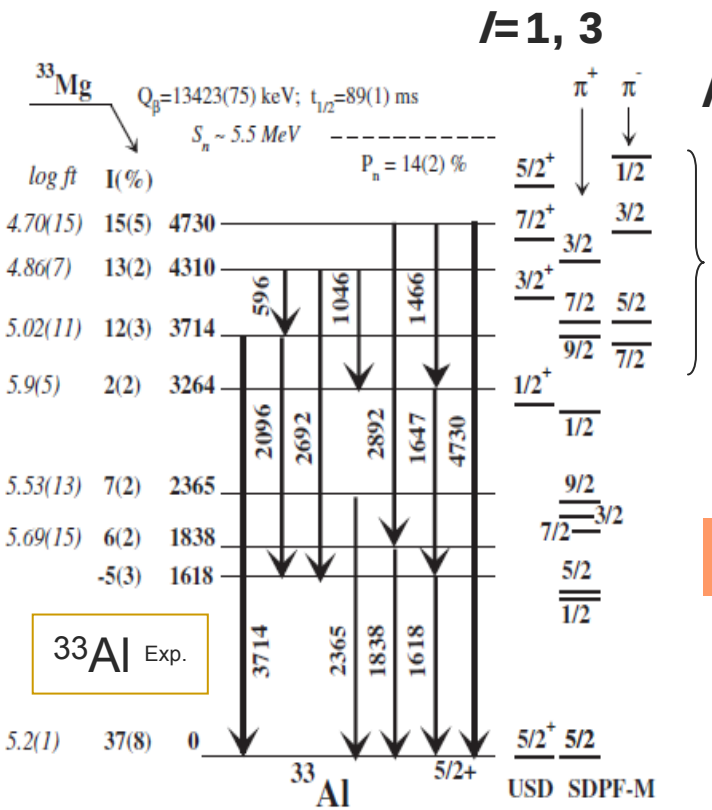
S(*l*=1) < 1.63, 60% upper limit

intruder configurations

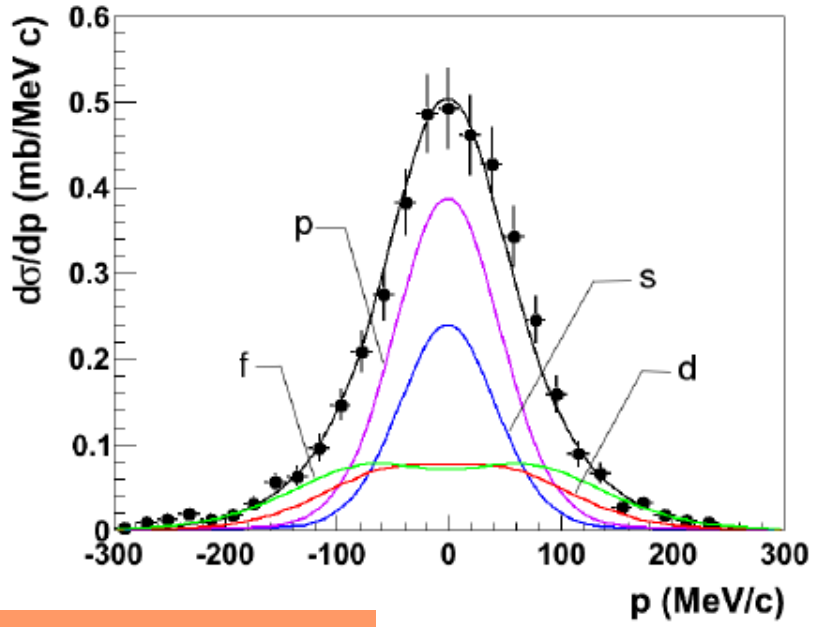
$^{34}Al \rightarrow n + {}^{33}Al$ at 880 MeV/u

σ_{-1n}= 81±4 mb , Γ_{FWHM}= 134±3 MeV/c

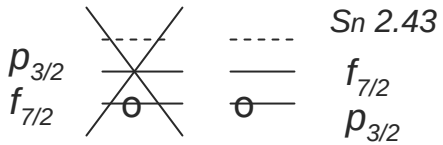
$^{34}Al_{g.s.}$ (4^-)



V. Tripathi *et al.*, PRL 101 (2008) 142504



$2p_{3/2}$ occupancy: 20-60%



N =20

^{34}Al

—— fit

S(l=0) < 1.45

S(l=1) = $0.97^{+0.10}_{-0.45}$

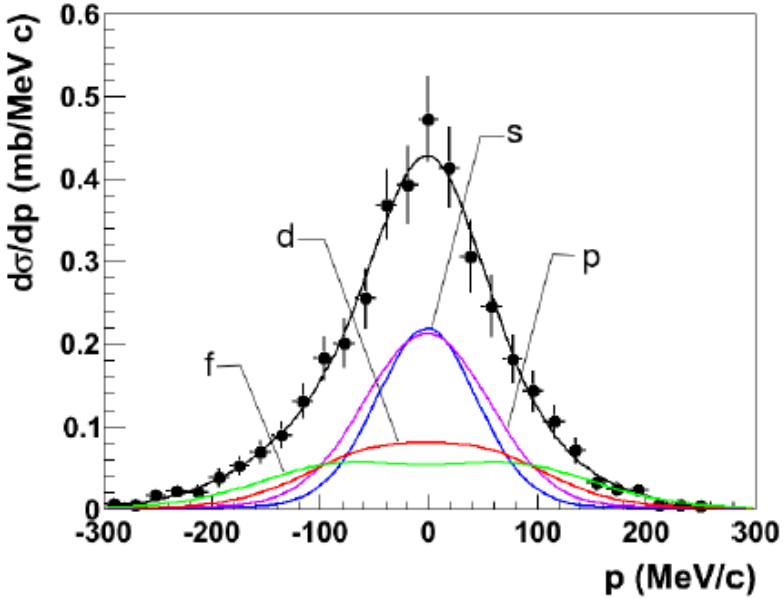
S(l=2) = $1.40^{+0.63}_{-0.58}$

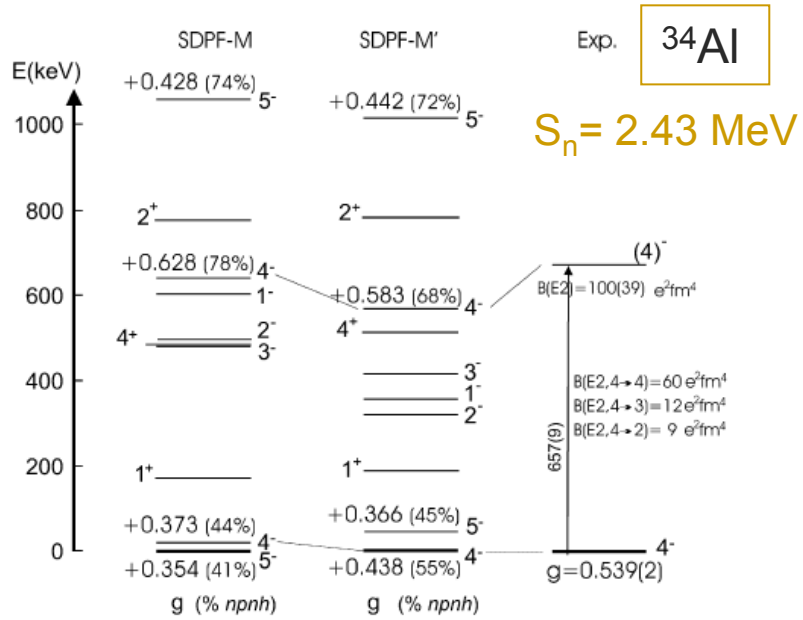
S(l=3) < 0.6

$^{35}Al \rightarrow n + ^{34}Al$ at 916 MeV/u

$^{35}Al_{g.s.}$ ($5/2^+$)

σ_{-1n}= 75±4 mb, Γ_{FWHM} = 145±3 MeV/c





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

	fit
S(*l*=0) =	$0.89^{+0.58}_{-0.89}$
S(*l*=1) =	$0.63^{+0.14}_{-0.28}$
S(*l*=2) =	$0.59^{+1.15}_{-0.59}$
S(*l*=3) =	$1.06^{+0.31}_{-0.39}$

----- *Sn 5.27*

$f_{7/2}$

$p_{3/2}$

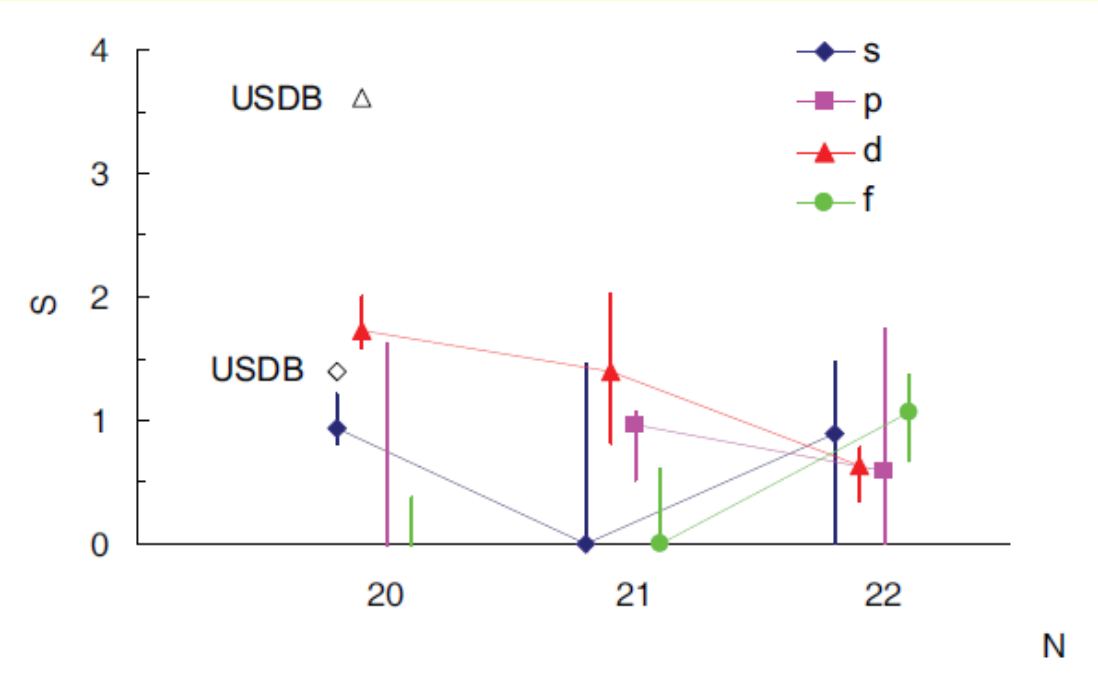
N =20

^{35}Al

$2p_{3/2}$ and $1f_{7/2}$ equally populated

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

Evolution of single particle neutron occupancy



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

Increasing *pf* occupancy

Summary

The evolution of the single particle occupancy in the $^{33,34,35}Al_{g.s.}$ studied through precise measurements of p// and σ_{-1n} performed at relativistic energies (≈900MeV/u) and compared with shell model predictions

- p// does not exclude the presence of intruder states in ^{33}Al (N=20)

  the inferred $2s_{1/2}$ neutron occupancy is 20-40% less than USDB predicted one

- 20-60% intruder l=1 occupancy found in ^{34}Al (N=21), in agreement with g factor measurement

  lowering of the $2p_{3/2}$ level , similar to ^{33}Mg

- $1f_{7/2}$ occupancy increases adding neutrons, and correspondingly $1d_{3/2}$ one decreases.

List of collaborators

T. Aumann[1], D. Boutin[2], B. A. Brown[4], D. Cortina-Gil[5], B. Davids[6], M. Diakaki[7], 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]

[1]*GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany*
[2]*Justus-Liebig University, Gießen, Germany*
[3]*Astronomy and Physics Department, Saint Mary's University, Halifax, Canada*
[4]*NSCL, Michigan State University, East Lansing, USA*
[5]*Universidad de Santiago de Compostela, Santiago de Compostela, Spain*
[6]*TRIUMF, Vancouver, Canada*
[7]*National Technical University, Athens, Greece*
[8]*Physik Department E12, Technische Universität München, Garching, Germany*
[9]*Faculty of Mathematics and Physics, Comenius University, Bratislava, Slovakia*
[10]*Fundamental Physics, Chalmers University of Technology, Göteborg, Sweden*
[11]*Università di Catania, Catania, Italy*
[12]*INFN-Laboratori Nazionali del Sud, Catania, Italy*
[13]*Center for Nuclear Study, University of Tokyo, Saitama, Japan*
[14]*Research Center for Nuclear Physics, Osaka, Japan*