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
  → $^{32-34}$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

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

C. Nociforo - "DREB12"
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.

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

Z=8 → Z=20, adding sd protons → wide N=20 gap

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

C. Nociforo - "DREB12"
Two-neutron separation energy $S_{2n}$

**Mg**

**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.

*C. Nociforo -"DREB12"*
**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

  \[ \sim 25\% \text{ in } ^{33}\text{Al and } 60\% \text{ in } ^{34}\text{Al, at least} \]

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


---

1n removal reactions test the neutron single particle structure

*C. Nociforo -“DREB12”*
1n removal reactions at relativistic energies

At high energy

\[ \frac{d\sigma}{dp_{\parallel}} = \int dr_{t} \left| \frac{1}{\sqrt{2\pi}} \int \varphi_0(r_{t}, z) e^{ip_{z}z} \right|^2 \int db D(b, r_{t}) \]

structure & reaction mechanism can be much easily disentangle

calculations: Glauber theory \[ \rightarrow \quad |\psi> = \text{core + neutron, eikonal approx.} \]

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

- Shape of \( \frac{d\sigma}{dp_{\parallel}} \) of the residual nucleus \( \rightarrow l_{n} \) of the removed nucleon
- Cross section \( \sigma_{-1n} \) \( \rightarrow \) spectroscopic factors

\[ \sigma_{-1n} = \sum_{l} S_{l} \sigma_{-1}^{\text{sp}}(\psi_{n lj} \otimes \mathcal{A}_{l}(I_{c}^{\pi})) \]

C. Nociforo - "DREB12"
Experimental technique

Relativistic energy RIBs advantages:
- thick target
- small forward scattering angles

FRAGMENT Separator (FRS)

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

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

$p_{lab} = B \rho \cdot q \cdot \left(1 + \frac{x_{F4} - C \cdot x_{F2}}{D_{F2-F4}}\right)$
$$^{33}\text{Al} \rightarrow \text{n} + ^{32}\text{Al} \text{ at } 922 \text{ MeV/u}$$

$$\sigma_{1n} = 64\pm3 \text{ mb, } \Gamma_{\text{FWHM}} = 136\pm3 \text{ MeV/c}$$

$^{33}\text{Al}_{g.s.} (5/2^+)$: shell model calc. (USDB)

- $C^2S = 1.40 \ (l=0)$ → 15-40% higher
- $C^2S = 3.61 \ (l=2)$

Adding $l=1, 3$ (p- and f-waves) does not change the results of the fit.

--- fit assuming $S(l=0) = 0$
- $S(l=1) < 1.63, 60\%$ upper limit
- Intruder configurations

C. Nociforo -"DREB12"
$^{34}\text{Al} \rightarrow n + ^{33}\text{Al}$ at 880 MeV/u

$^{34}\text{Al}_{g.s.}(4^{-})$

$l=1, 3$

$l=0, 2$

with negative parity core states

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

$\sigma_{1n} = 81\pm4$ mb, $\Gamma_{\text{FWHM}} = 134\pm3$ MeV/c

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

C. Nociforo - "DREB12"
$^{35}\text{Al} \rightarrow n + ^{34}\text{Al}$ at 916 MeV/u

$\sigma_{-n} = 75\pm 4 \text{ mb}$, $\Gamma_{\text{FWHM}} = 145\pm 3 \text{ MeV/c}$

$^{34}\text{Al}$

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

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

C. Nociforo - "DREB12"

$^{34}\text{Al}_{\text{g.s.}} (5/2^+)$

$S_n = 2.43 \text{ MeV}$

$\sigma_{2p/3f} = 75\pm 4 \text{ mb}$,
$\Gamma_{\text{FWHM}} = 145\pm 3 \text{ MeV/c}$

$N = 20$

$2p_{3/2}$ and $1f_{7/2}$ equally populated
Mixing in $^{33-35}\text{Al}$

**Evolution of single particle neutron occupancy**

33Al  34Al  35Al

Increasing $pf$ occupancy

C. Nociforo - "DREB12"
The evolution of the single particle occupancy in the $^{33,34,35}$Al$_{g.s.}$ studied through precise measurements of $p//_n$ and $\sigma_{-1n}$ performed at relativistic energies ($\approx 900$MeV/u) and compared with shell model predictions.

- $p//_n$ 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.

*C. Nociforo - "DREB12"*
List of collaborators

T. Aumann¹, D. Boutin², B. A. Brown⁴, D. Cortina-Gil⁵, B. Davids⁶, M. Diakaki⁷, F. Farinon¹,², H. Geissel¹, R. Gernhäuser⁸, R. Janik⁹, B. Jonson¹⁰, R. Kanungo³, B. Kindler¹, R. Knöbel¹,², R. Krücken⁸, N. Kurz, M. Lantz¹⁰, H. Lenske², Yu.A. Litvinov¹, K. Mahata¹, P. Maeirbeck⁸, A. Musumarra¹¹,¹², T. Nilsson¹⁰, T. Otsuka¹³, C. Perro³, A. Prochazka¹,², C. Scheidenberger¹,², B. Sitar⁹, P. Strmen⁹, B. Sun², I. Szarka⁹, I. Tanihata¹⁴, H. Weick¹, M. Winkler¹

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

C. Nociforo -"DREB12"