Evolution of the neutron 1d spin-orbit splitting in ^{35}S and ^{39}Ca

S. Jongile

iThemba Laboratory for Accelerator Based Sciences, Old Faure Road Faure, Somerset West PO Box 722 Somerset West, 7129 South Africa

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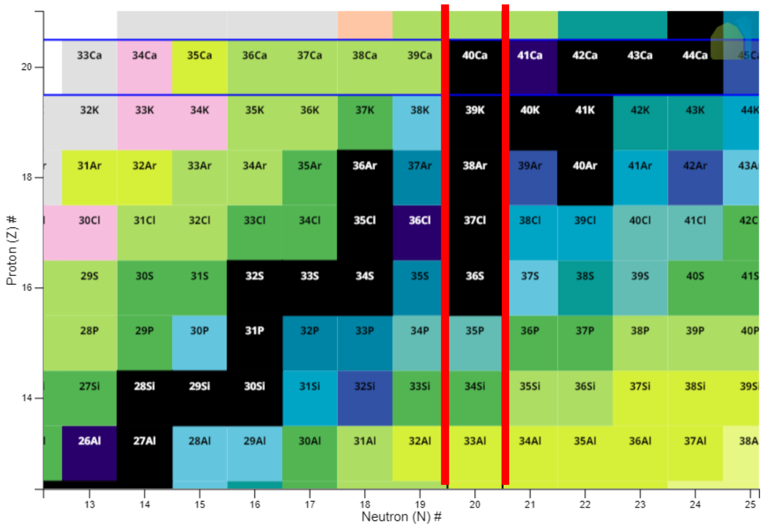
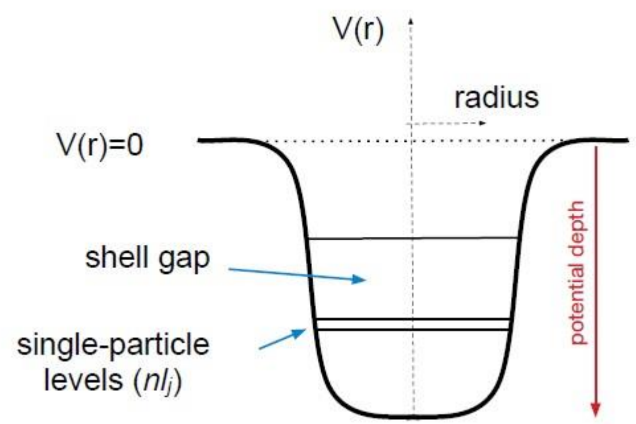
Shell evolution/ changes of magic nuclei: Which underlying forces ?

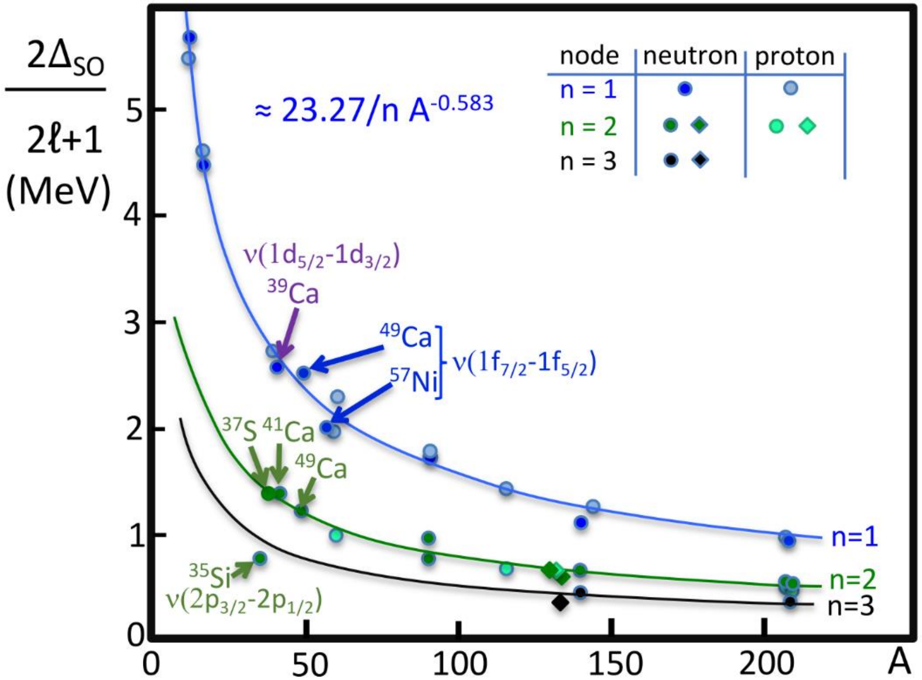
Simplified mean-field





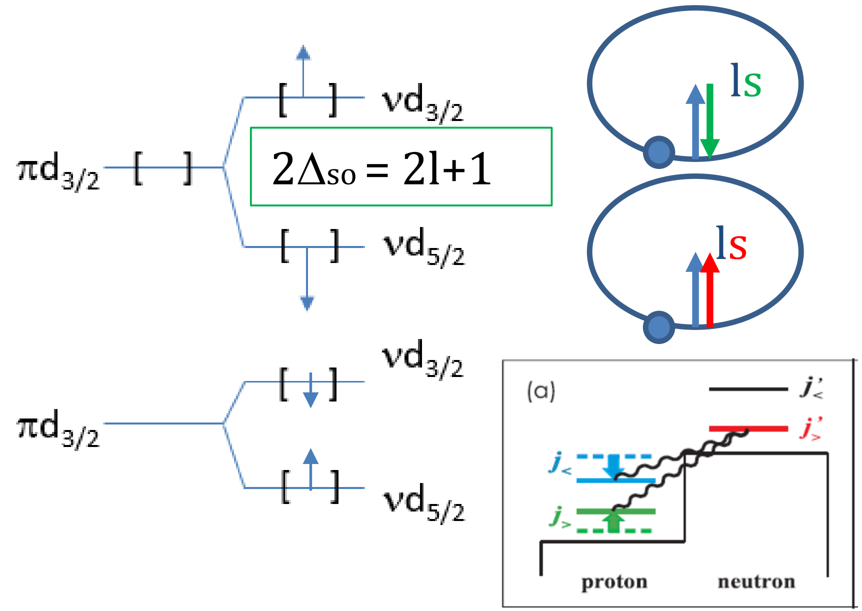
- Most neutron shell gaps remain remarkably stable under the removal of few protons.
- A sudden reduction of the shell gap or inversion of the position of neutron shells, have been identified when removing few more protons from a specific shell.
- Remarkable signatures to date are the disappearances of the neutron magic numbers 8, 20 and 28 for nuclei with a large N to Z imbalance.

Evolution of the spin-orbit splitting



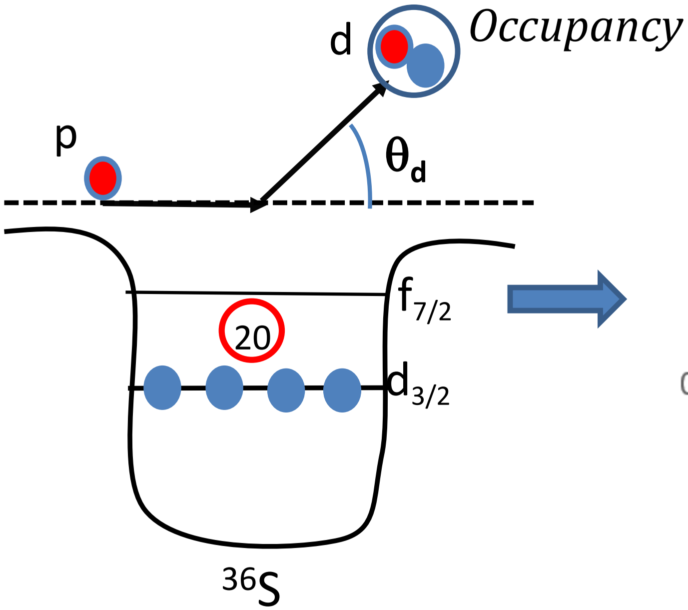
G. Mairle et al., PLB 304 (1993) 39

Effect of Tensor Force

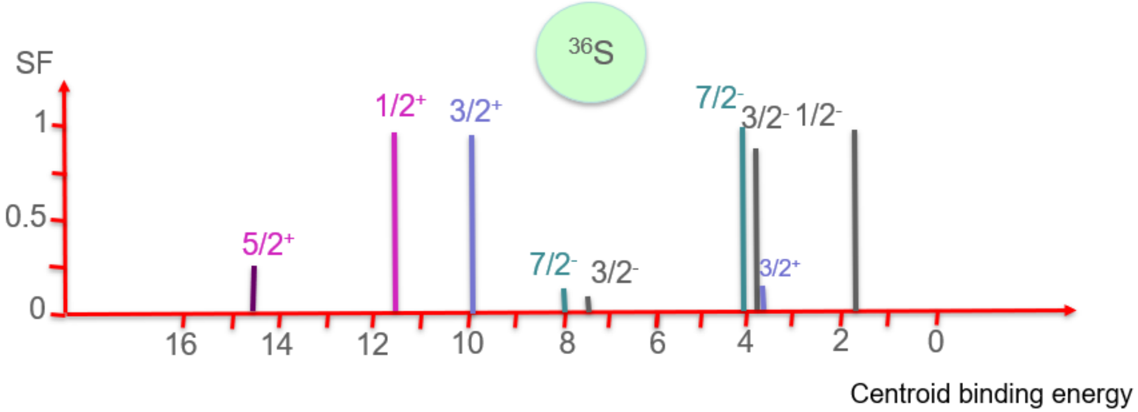


T. Otsuka et al., Phys. Rev. Lett. 95, 232502 (2005) demonstrates well the action of the tensor force

Transfer reaction: a tool to study the shell evolution



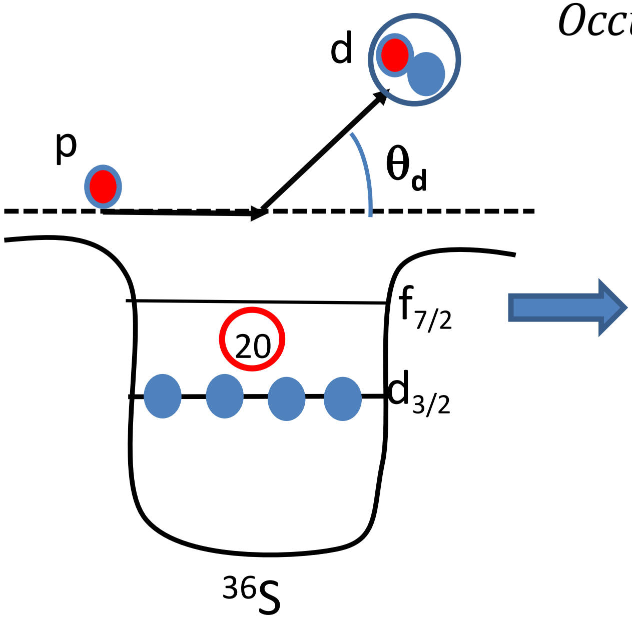
- ✓ AIM: to study the neutron $d_{5/2}$-$d_{3/2}$ spin orbit splitting in ^{35}S and compare to ^{39}Ca [1]



- ✓ *Ed* –centroid binding energy of the respective orbit
- ✓ θ_p -orbital momentum L from where a nucleon is removed from
- ✓ *Cross section* –Gives the C^2S^- values hence occupation number of the orbit

[1] M. Matoba et al.,Phys. Rev. C 48, 95 **(1993).**

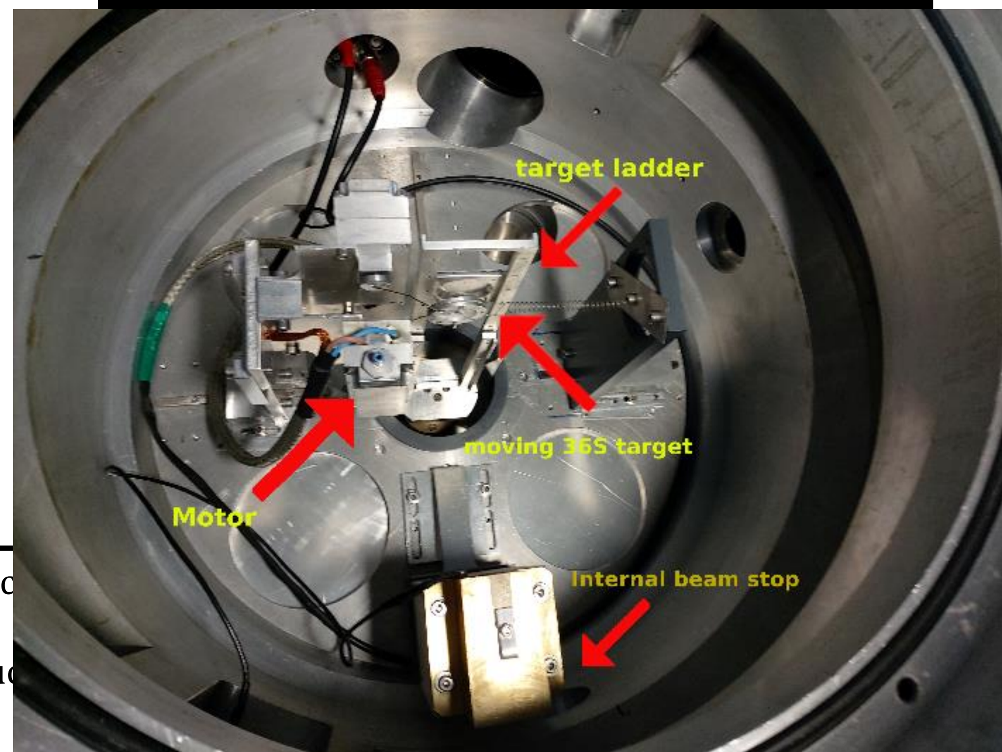
Transfer reaction: a tool to study the shell evolution



Occupancy

- ✓ AIM: to study the neutron $d_{5/2}$-$d_{3/2}$ spin orbit splitting in ^{35}S and compare to ^{39}Ca [1]

Developed innovative target solution



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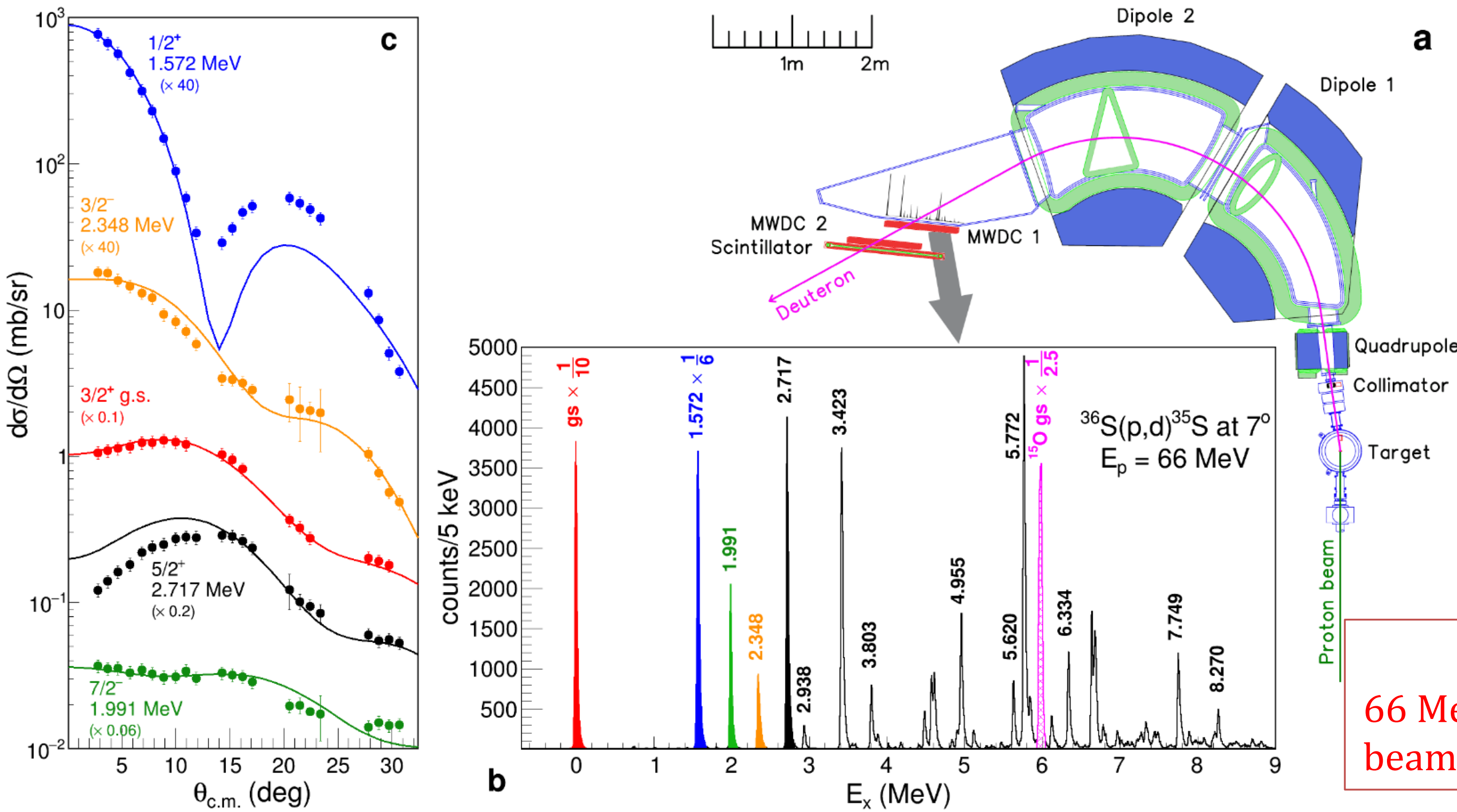
$^{36}S(p,d)^{35}S$ K600 Experiment

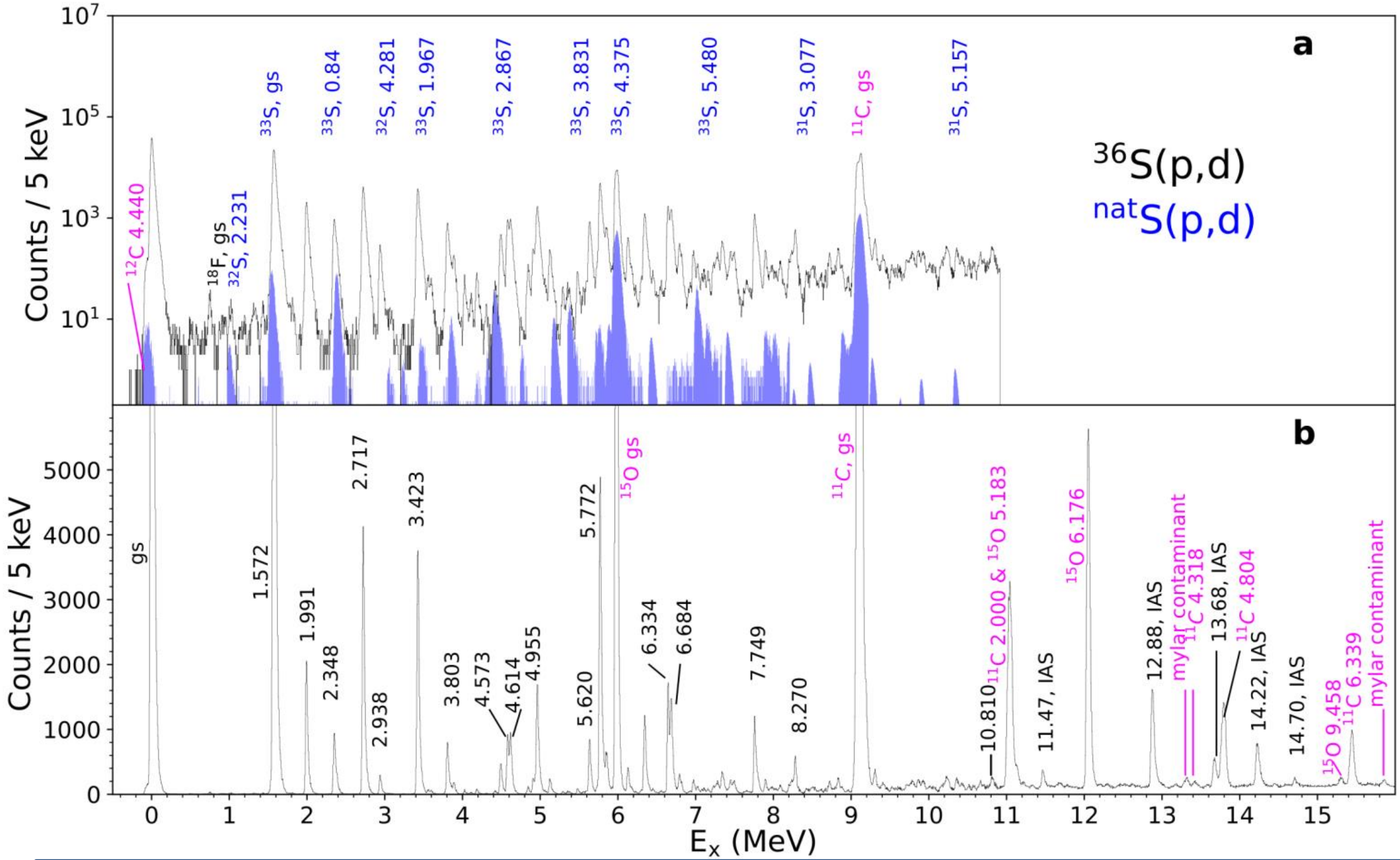


66 MeV proton beam from SSC

- **K600 spectrometer – recoil identification with~30 keV energy resolution**
- **Data was collected at 4º, 7º, 10º, 15º, 21º and 28º**

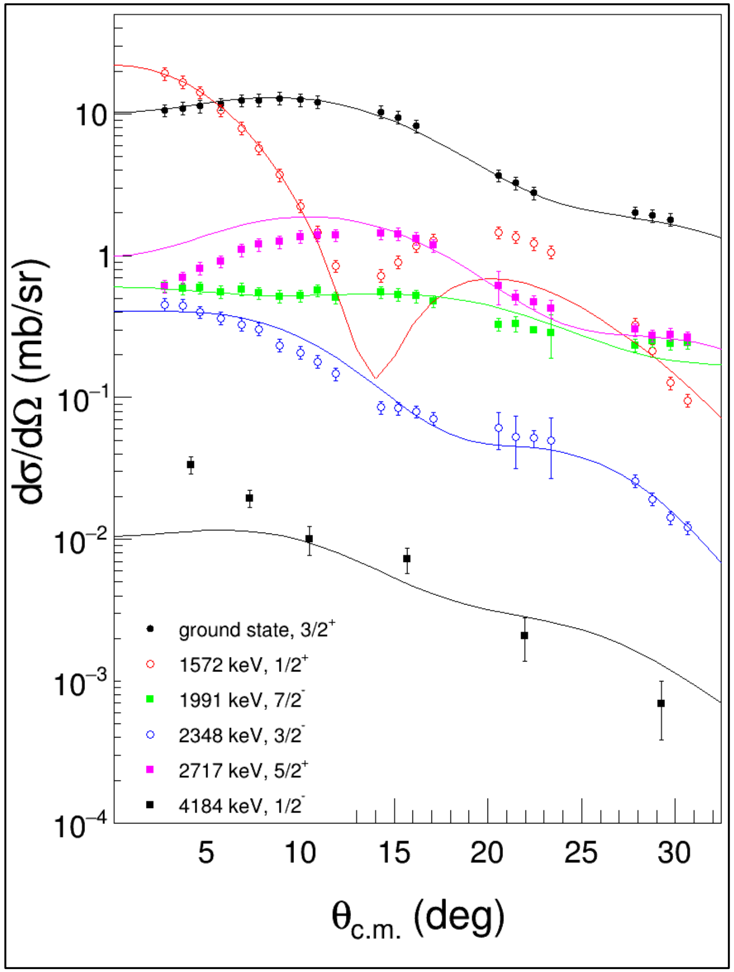
Identifying states in ^{35}S

$^{36}S(p,d)$ at 7°

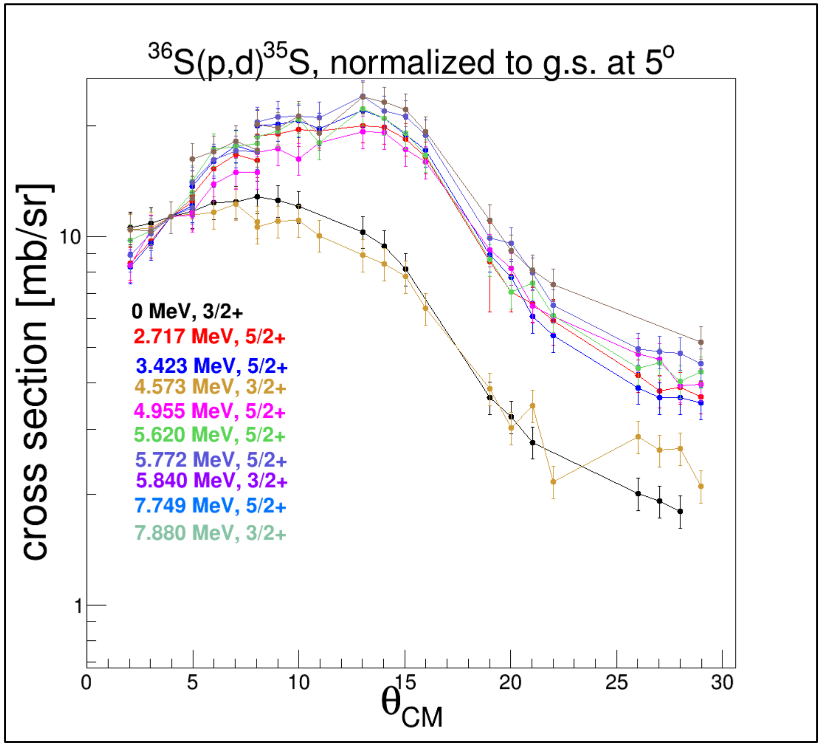


- ✓ Three overlapping magnetic field settings used to cover excitation energy range up to 14.7 MeV.
- ✓ Other sulfur isotopes do not affect the states of interest (negligible contamination)

DWBA calculations



j-dependence



j-dependence not expected however it was clearly observed.
It was observed also in a previous study [2]

Theory by Nicholas Keeley and Freddy Flavingy

[2] R. L. Kozub, Phys. Rev. 172, 1078 (1968).

$d_{5/2}$,$d_{3/2}$ spectroscopic strengths

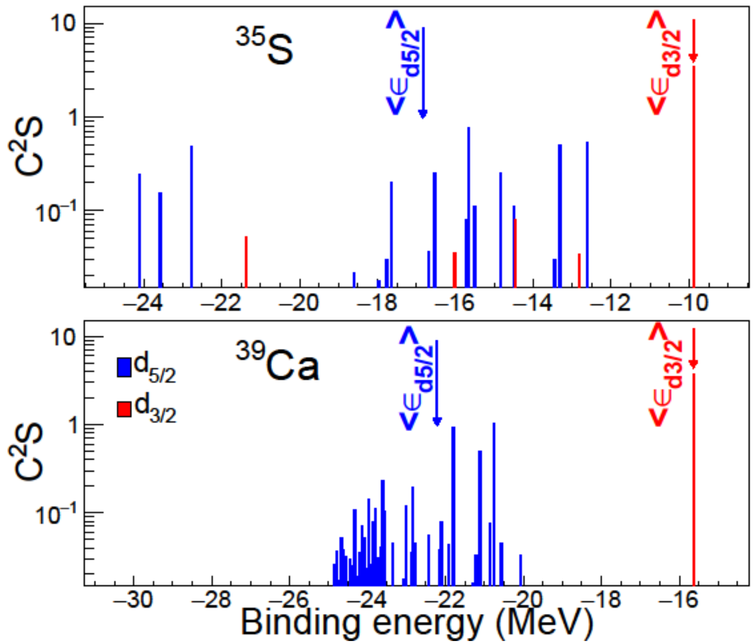
Strength fragmentation

C^2S^- Weighted mean energies

$$E = \frac{\sum C^2S^-(j) \, . Ex}{\sum C^2S^-}$$

Centroid energies

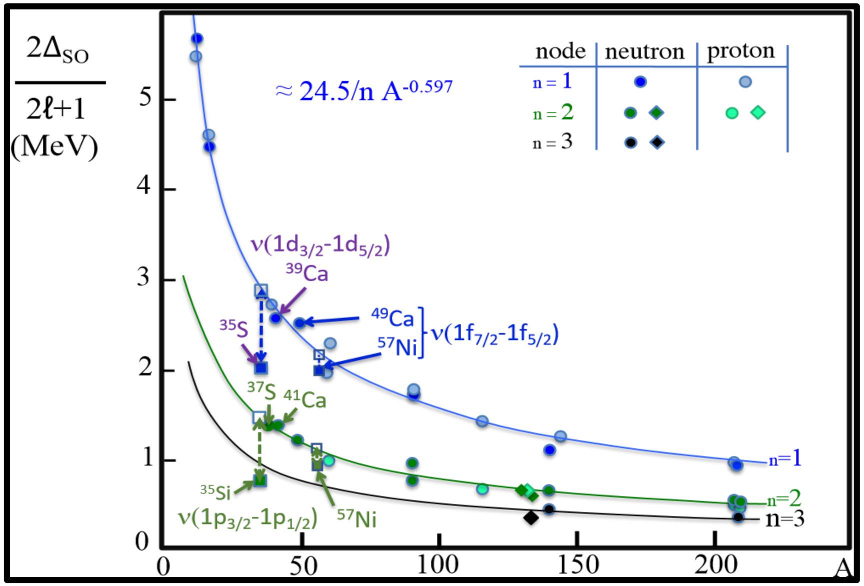
$$< \epsilon_j > = -Sn(^{36}S) + E$$

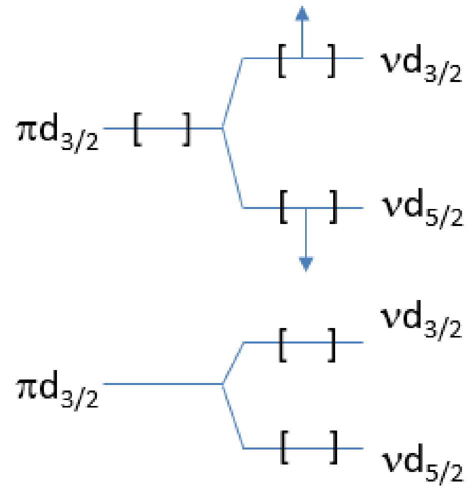


- Centroid binding energies allow for the extraction of the magnitude of the SO splitting
- We determined the spectroscopic strength distributions for the $d_{5/2}$ and $d_{3/2}$ orbits and centroid binding energies, as determined in the (p, d) neutron removal reaction for ^{35}S and ^{39}Ca [1] nuclei

[1] M. Matoba et al.,Phys. Rev. C 48, 95 **(1993).**

Spin-orbit splitting





Reduction in spin-orbit splitting from ^{39}Ca to ^{35}S

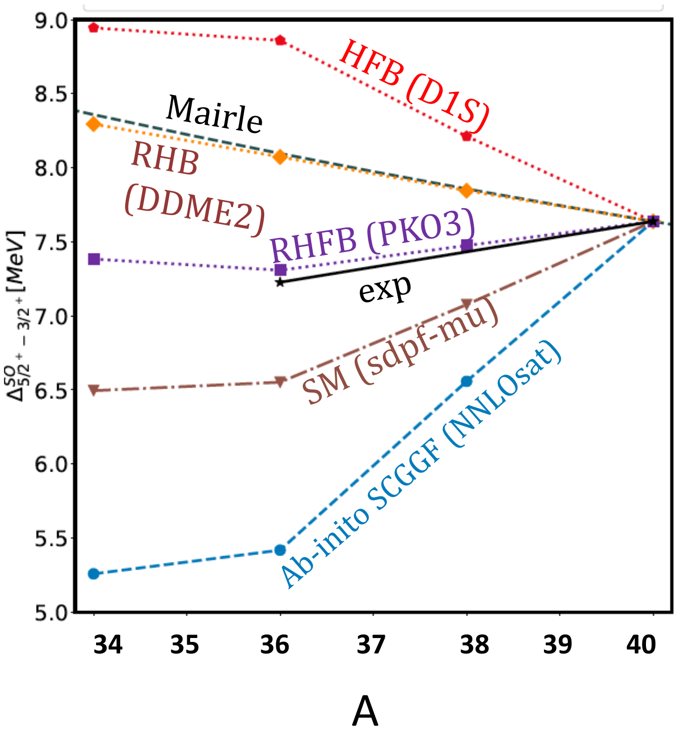
$\frac{\sum C^2S\ .Ex}{\sum C^2S}$ = 6.527 MeV in ^{35}S and 6.580 MeV in ^{39}Ca

- ✓ This is consistent with a reduction in spin-orbit splitting of 0.053 MeV
- ✓ Including the C^2S^+ results it is further enhanced to 0.411 MeV
- ✓ From (d,p)[3,4] we have C^2S^+ and (p,d) we have C^2S^-

[3] G. Burgunder et al.,Phys. Rev. Lett. 112, 042502 (2014).

[4]. Nesaraja and E. McCutchan, Nuclear Data Sheets 133, 1 (2016).

Answer: The tensor force?



Comparison between theory, Mairle's trend and present data

Theory: J. P. Ebran, V. Soma, T. Duguet, C. Yuan

- **MF** and **RMF** theories (without tensor forces) predict a decrease of SO between ^{36}S and ^{40}Ca
- **Shell-model** and **Ab-inito** models predict a strong increase of SO splitting owing to tensor force. Experiment lies in the middle.
- **PKO3** interaction (which implements tensor force) gives an excellent agreement with experiment.

Summary

- A total of **98 states** identified and **47 new** states
- C^2S^- extracted for **81 states**.
- States in ^{35}S identified up to 14.7 MeV including IAS states
- Experiment gives good constraint to indicate effect of the tensor force.
- Experiment agrees well with theory that includes tensor force.

THANK YOU!

Members of the Collaboration

S. Jongile,[1,2] M. Wiedeking,[1,3] O. Sorlin,[4] R. Neveling,[1] N. Keeley,[5] T. Duguet,[6,7] J.P. Ebran,[8] V. Somà,[6] C. Yuan,[9] A. Lemasson,[4] P. Papka,[2,1] P. Adsley,[10,1] A.A. Avaa,[1,3] F. Azaiez,[1] L.M. Donaldson,[1] F. Flavigny,[11] H. Jivan,[3,] 1 P. Jones,[1] D. Kenfack,[1,2] N.Y. Kheswa,[1] T.C. Khumalo,[1,3] A.O. Macchiavelli,[12] L. Makhathini,[1,2] K.L. Malatji,[1,2] S.H. Mthembu,[1,13] F. Nemulodi,[1] A.A. Netshiya,[1,3,14] L. Pellegri,[1,3] F.D. Smit,[1] and C. Vandevoorde[1]

1. iThemba Laboratory for Accelerator Based Sciences, Old Faure Road, PO Box 722, 7129 Somerset West, South Africa
2. Stellenbosch University, Private Bag X1, Matieland, 7602 Stellenbosch, South Africa
3. University of the Witwatersrand, Private Bag2050 Johannesburg, South Africa
4. Grand Acc´el´erateur National d'Ions Lourds (GANIL), CEA/DRF - CNRS/IN2P3, B. P. 55027, F-14076 Caen Cedex
5. France 5National Centre for Nuclear Research, ul. Andrzeja So ltana 7, 05-400 Otwock, Poland
6. IRFU, CEA, Universit´e Paris-Saclay, 91191 Gif-sur-Yvette, France
7. KU Leuven, Instituut voor Kern- en Stralingsfysica, 3001 Leuven, Belgium
8. CEA,DAM,DIF, F-91297 Arpajon, France
9. Sino-French Institute of Nuclear Engineering and Technology, Sun Yat-Sen University, Zhuhai, 519082 Guangdong, China
10. Texas AM University, College Station, Texas 77843, USA
11. CEA, Centre de Saclay, IRFU/Service de Physique Nucl´eaire, F-91191 Gif-sur-Yvette, France and Instituut voor Kern- en Stralingsfysica, KU Leuven, B-3001 Leuven, Belgium.
12. Oak Ridge National Laboratory, 1 Bethel Valley Road Oak Ridge, TN 37830, USA 13University of the Western Cape, Robert Sobukwe Rd, Bellville, 7535 South Africa