Nuclei in the upper *sd* shell and evolution of *sd-fp* shell gap

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Why study nuclei in the sd shell

- has been studied since 1960s.
  - •mostly low spin states :observation of spherical as well as deformed states
  - •experimental limitations in the sensitivity and efficiency of the detection system.
  - •Shell model calculations limited by severe truncation.
- In the recent years, sophisticated techniques of gamma spectroscopy permitted
  - •observation of high spin states of several nuclei.
    - •states of pure shell model characteristics coexisting with those with features of permanent deformation : Superdeformation in ^{40}Ca & ^{36}Ar,
    - • Violation of Mirror Symmetry observed.

•The nuclei in the neighbourhood of doubly closed ^{40}Ca are suitable

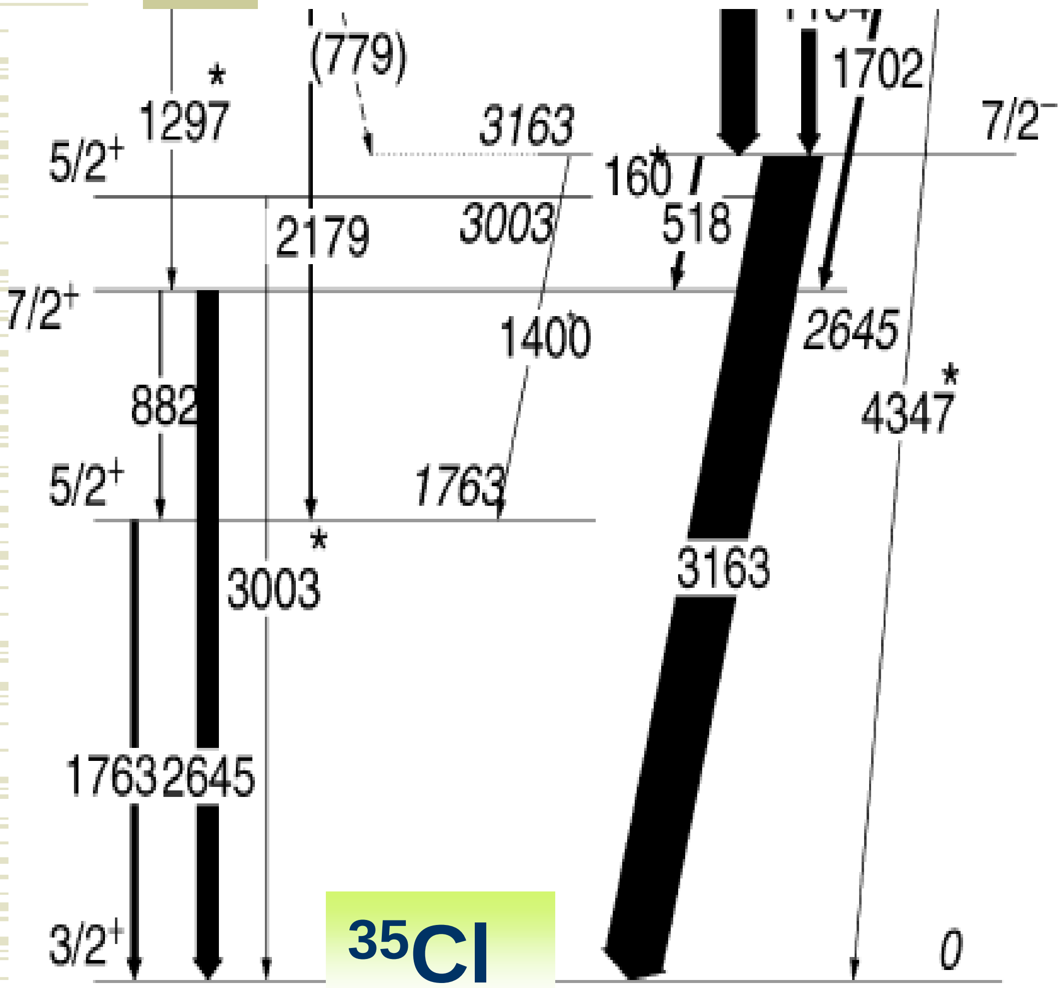
- •for applications of spherical shell model calculations.
- •The SD band provides an ideal opportunity to extend the microscopic description of collective rotation from the single-shell rotors like ^{20}Ne, ^{24}Mg, and ^{48}Cr to a case involving the cross-shell correlations characteristic of rotational motion in heavier nuclei.

•Indications of breaking of a shell closure (near N = 20) far from stability have been observed in ^{31}Na, ^{32}Mg - in the "island of inversion”.

Gamma Spectroscopy in A~40 region

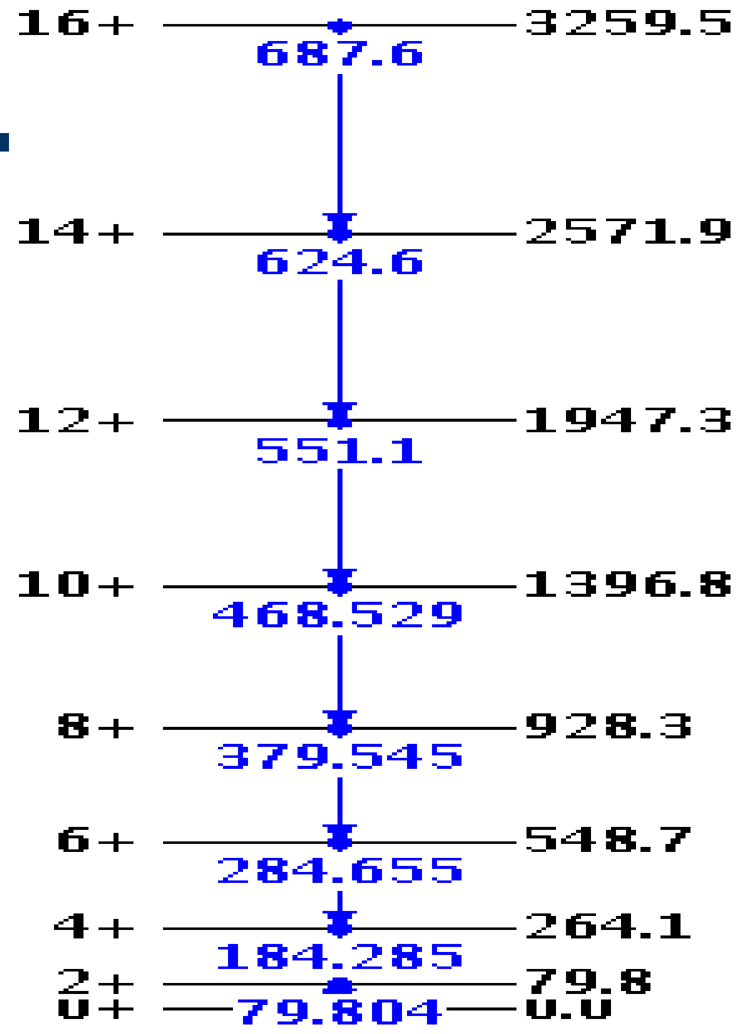
- The gamma spectroscopic studies of these light mass nuclei are very much different from those of the heavier ones.
- The light nuclei have lower Coulomb barriers, so the number of competing channels with **evaporation of charge particles becomes very large** with increasing excitation energy of the compound nucleus.
- As in most of the cases the **structure of these nuclei are dominated by shell model states**, these are low multiplicity experiments. Low level density.
- The valence space of the nucleons does not contain high spin orbitals (highest spin orbital is $1f_{7/2}$). So the **angular momentum of the compound system is also restricted.** The light masses of the reaction products in the fusion reaction also result in lower angular momentum.
- The transition energies are usually very high (~ 2-3 MeV) where the efficiencies of the normal HPGe detectors fall o very sharply. As the spin increases, the energies of the transitions become higher implying lower detection efficiency and poorer resolution. In this respect the **Clover detectors in their addback mode show excellent improvement** over the normal detectors.

Low multiplicity experiments

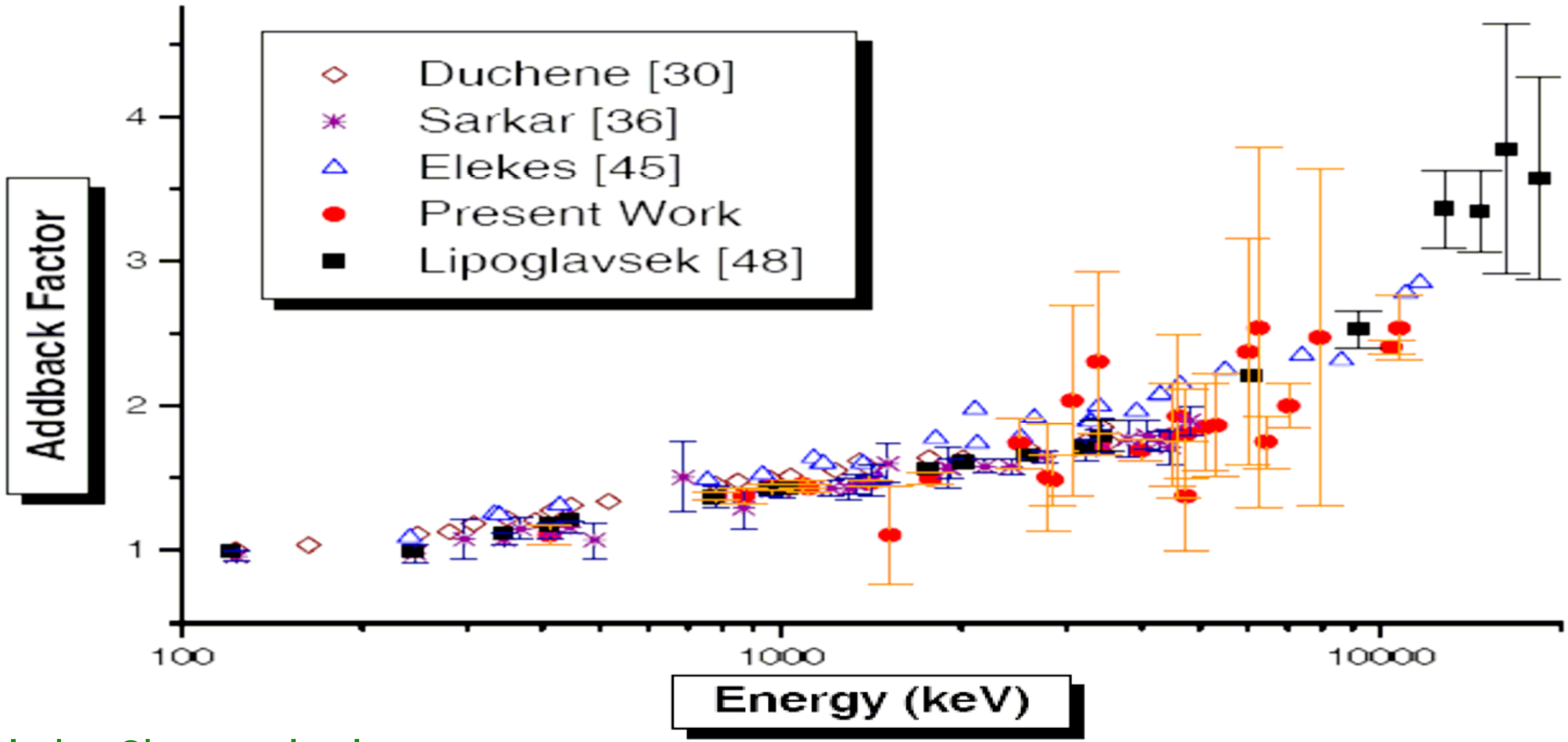


^{35}Cl

^{168}Er



Variation of Addback with energy

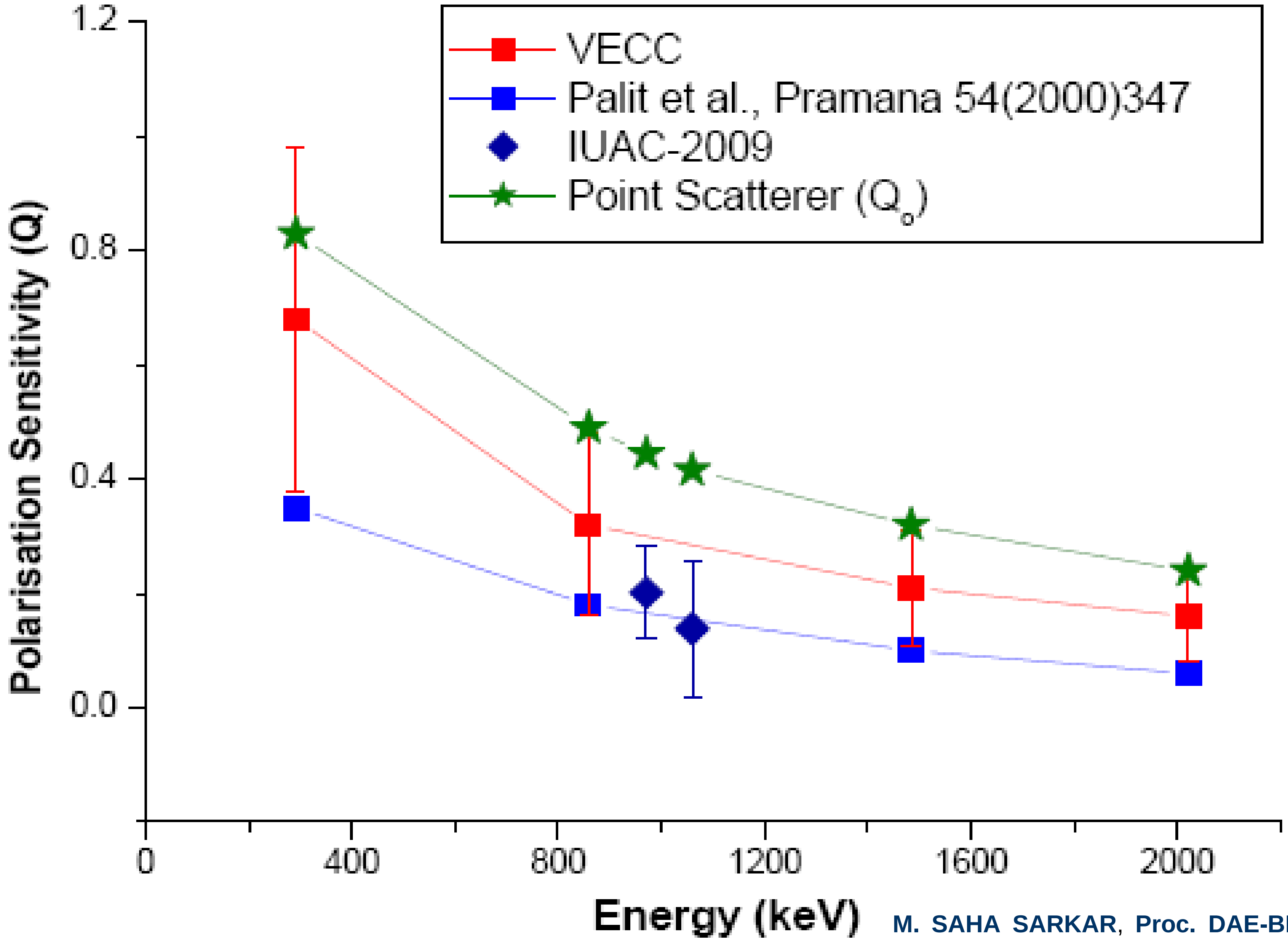


Prelude : Characterisation of the Clover Detector

G. Duchˆene et al. Nucl. Instr. and Meth. A 432, (1999) 90, Z. Elekes et al., Nucl. Instr. and Meth. A 503 (2003) 580. M. Lipoglavˇsek *et al.*, Nucl. Instr. and Meth. A 557, (2006) 523; (10 to 20.7 MeV)

M. Saha Sarkar et al., Nucl. Instr. & Meth. A491 (2002) 113.

M. Saha Sarkar et al., Nucl. Instr. & Meth. A556 (2006) 266.

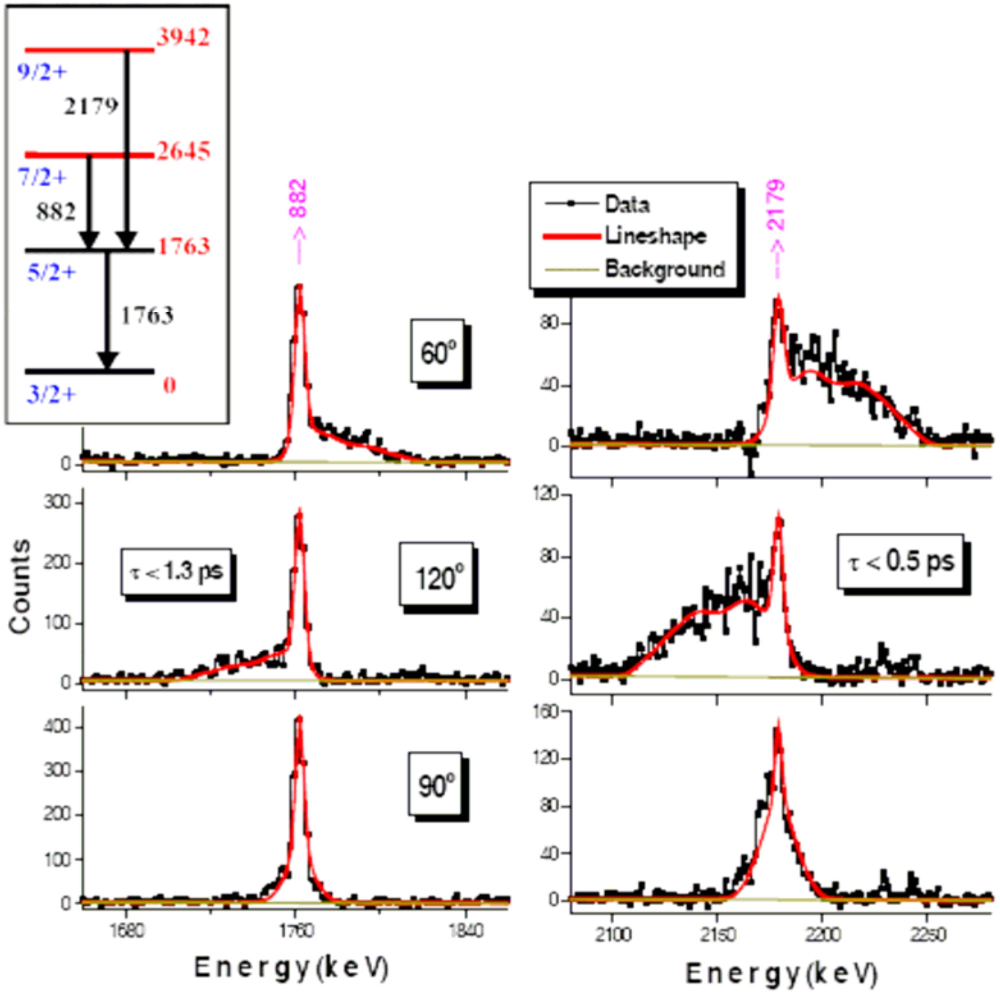


M. SAHA SARKAR, Proc. DAE-BRNS Symp. Nucl. Phys. (India) 55 (2010) I19 (http://www.sympnp.org/proceedings/index.php: electronic version only)

Polarisation sensitivity of different implementations of INGA

High spin structure of ^{35}Cl

***High spin structure of ^{35}Cl and the sd–fp shell gap*,** Ritesh Kshetri, **M. SAHA SARKAR**, Indrani Ray, P. Banerjee, S. Sarkar, Rajarshi Raut, A. Goswami, J. M. Chatterjee, S. Chattopadhyay, U. Datta Pramanik, **A.** Mukherjee, C. C. Dey, S. Bhattacharya, B. Dasmahapatra, Samit Bhowal, G. Gangopadhyay, P. Datta, H.C. Jain, R. K. Bhowmik, S. Muralithar, R. P. Singh, R. Kumar. **Nucl. Phys. A 781 (2007) 277.**



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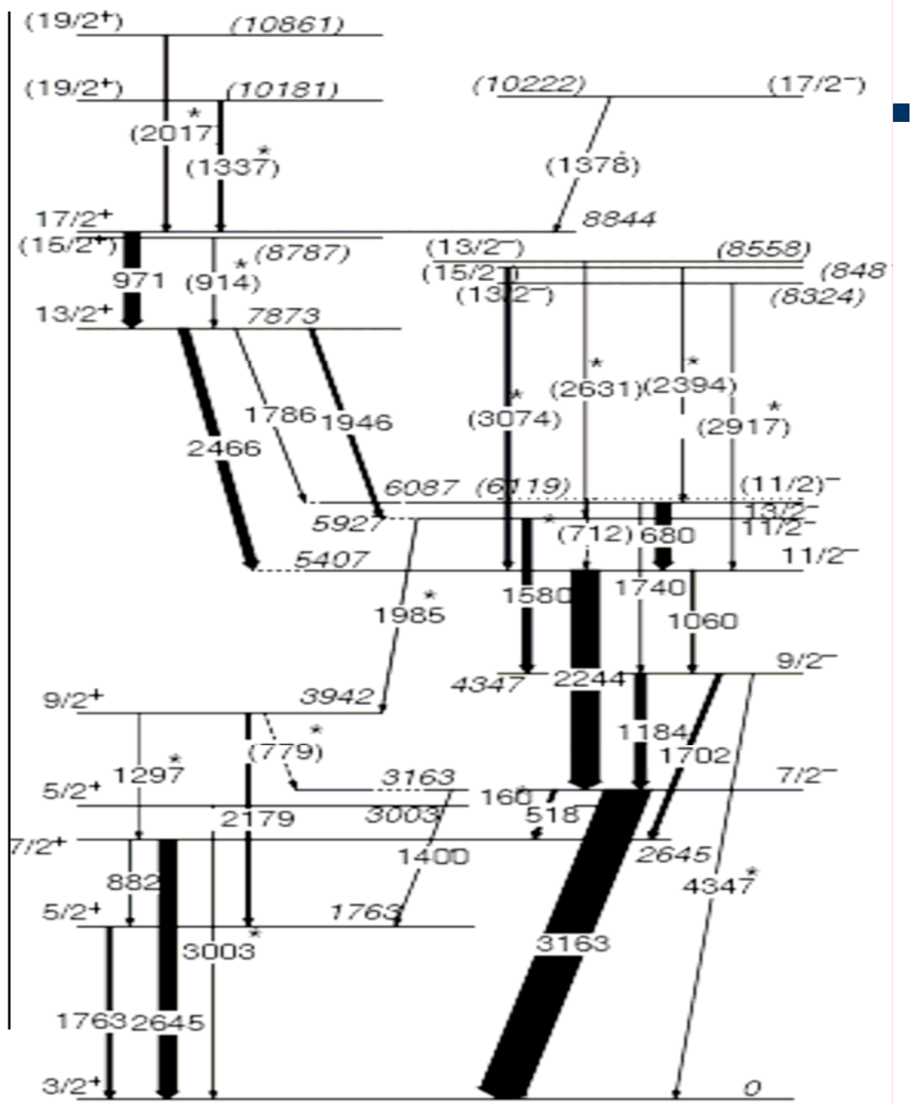
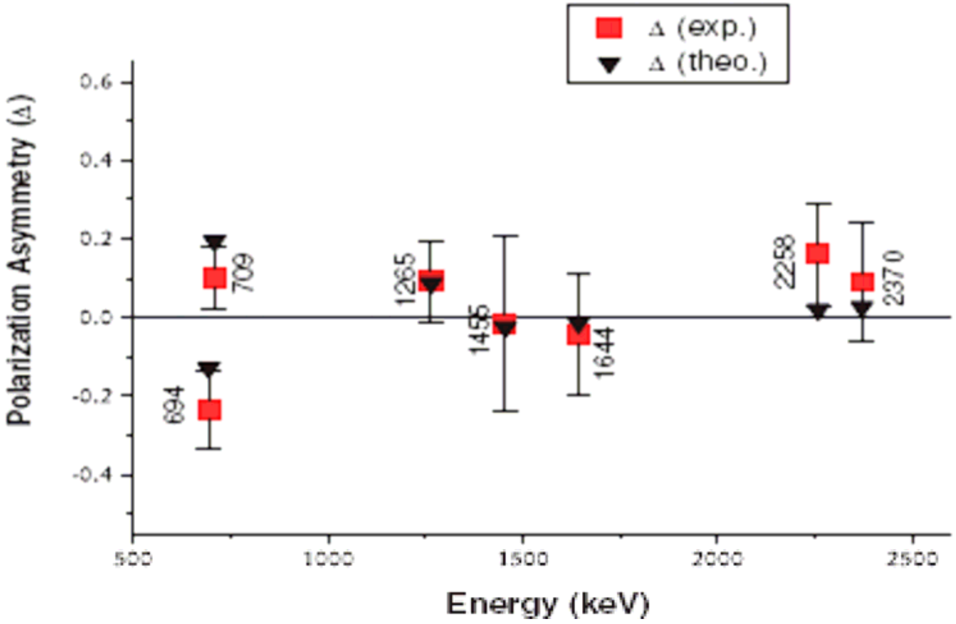


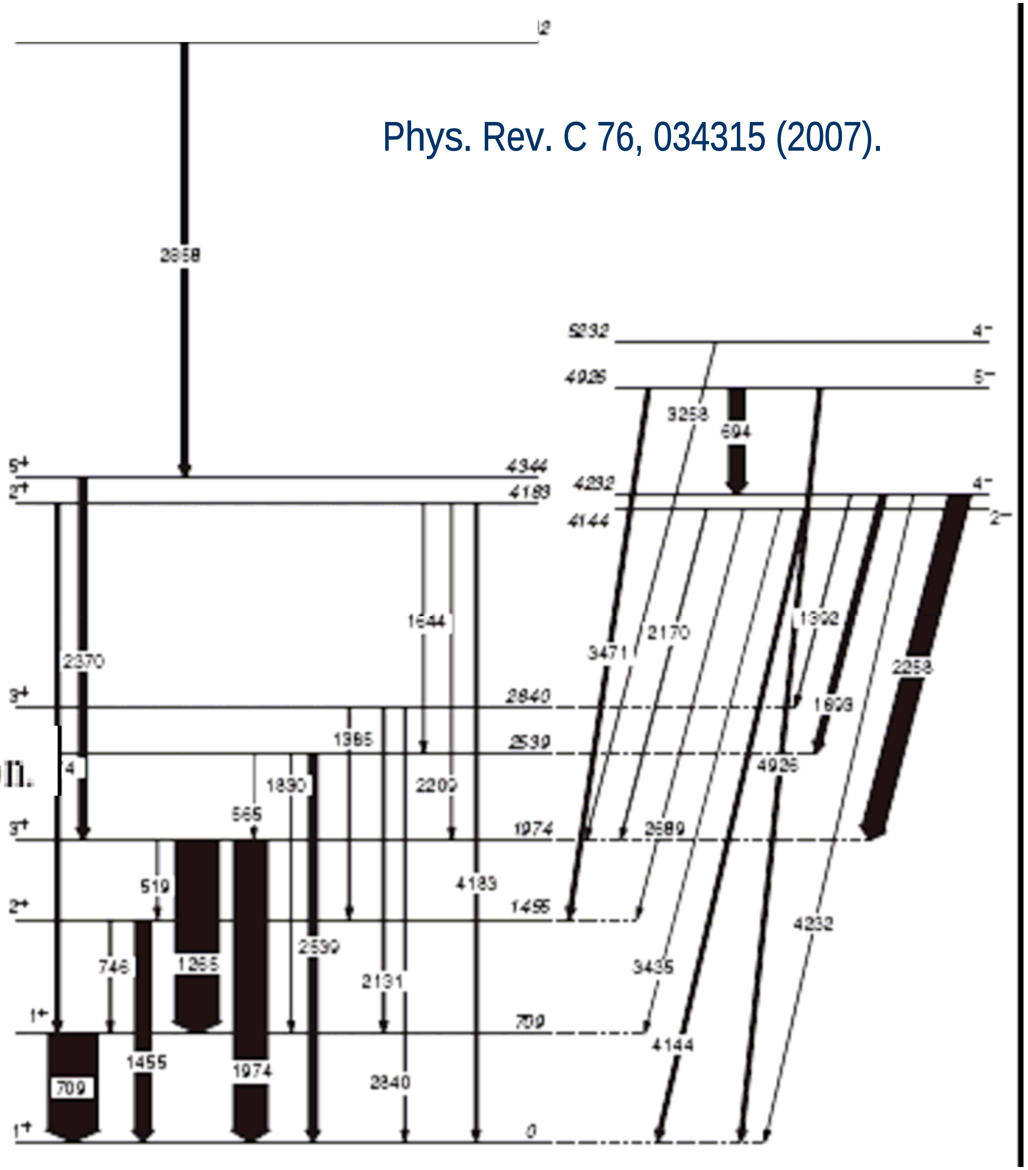
Gamma spectroscopic study of ^{30}P



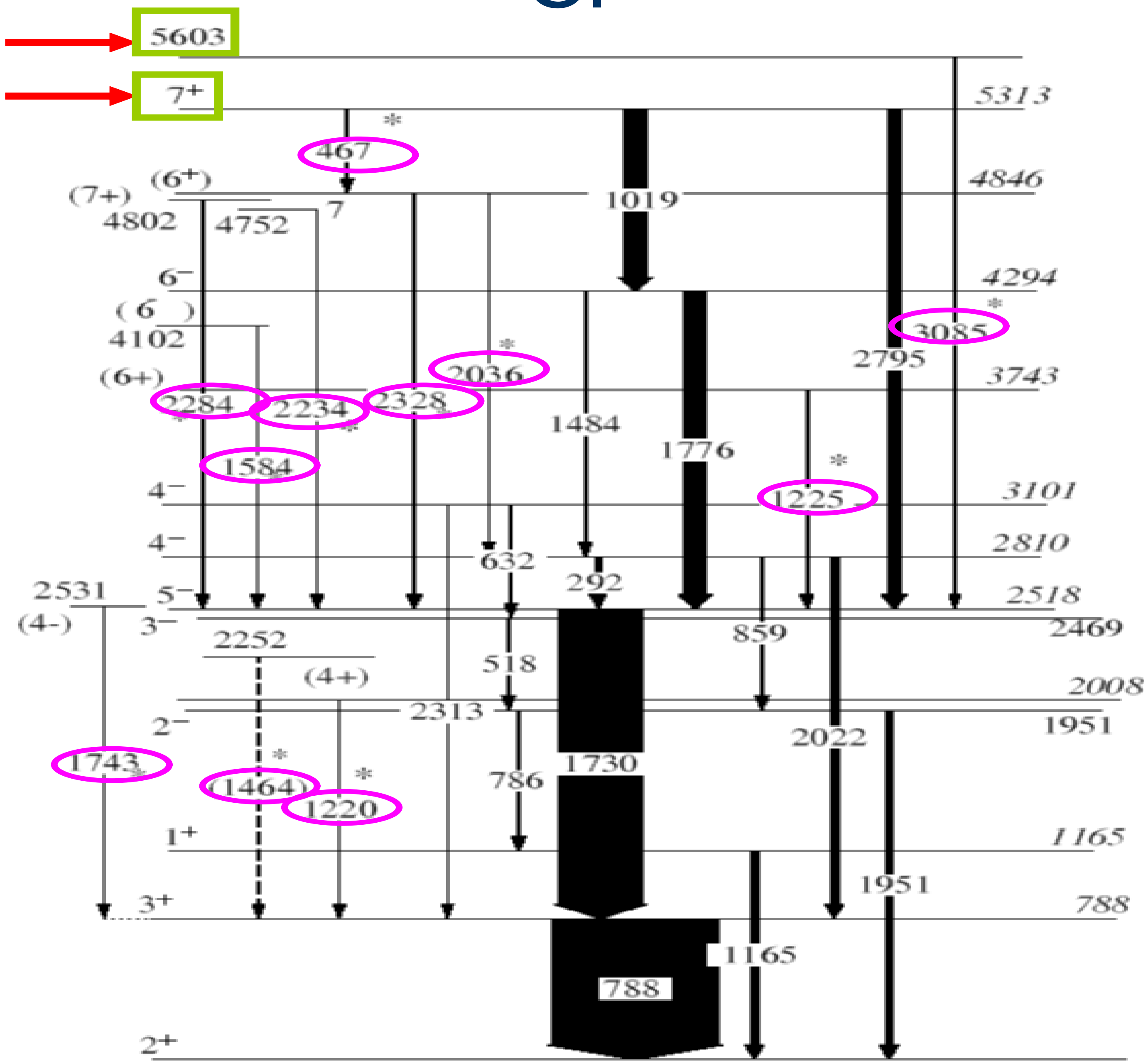
The nucleus ^{30}P was populated in the $^{16}O(^{16}O,pn)$ reaction.

Indication of the onset of collectivity in ^{30}P, Indrani Ray, Moumita Roy Basu, Ritesh Kshetri, M. SAHA SARKAR, S. Sarkar, P. Banerjee, S. Chattopadhyay, C.C. Dey, A. Goswami, J. M. Chatterjee, A. Mukherjee, S. Bhattacharya, B. Dasmahapatra, P. Datta, H.C. Jain, R. K. Bhowmik, S. Muralithar, R. P. Singh, Phys. Rev. C 76, 034315 (2007).

Phys. Rev. C 76, 034315 (2007).



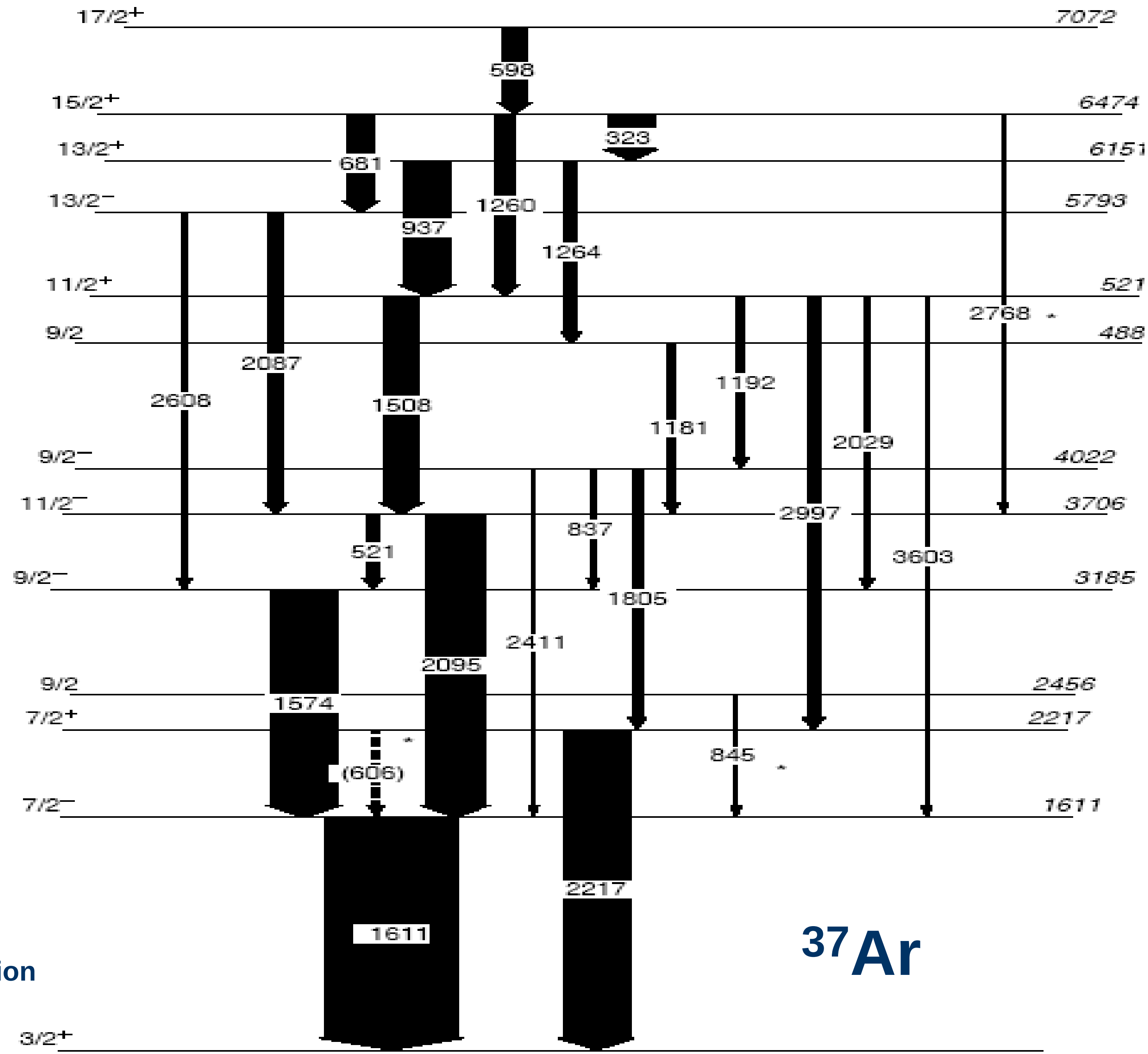
^{36}Cl



Sudatta Ray, I. Ray, Ritesh Kshetri, R. Raut, S. Ganguly, M. K. Pradhan, D. Kanjilal, M. Ray Basu, A. Chakraborty, Krishichayan, A. Mukherjee, G. Ganguly, S.S. Ghugre, S. Bhattacharya, P. Banerjee, A. Goswami, A. Deo, S.Kumar, H. C. Jain, I.Mazumdar, R.Palit, S. Sarkar, **M. SAHA SARKAR,** Proc. DAE-BRNS Symp. Nucl. Phys. (India) 53 (2008) 353.

M. SAHA SARKAR, Proc. DAE-BRNS Symp. Nucl. Phys. (India) 55 (2010) I19 (http://www.sympnp.org/proceedings/index.php: electronic version only)

Manuscript under preparation



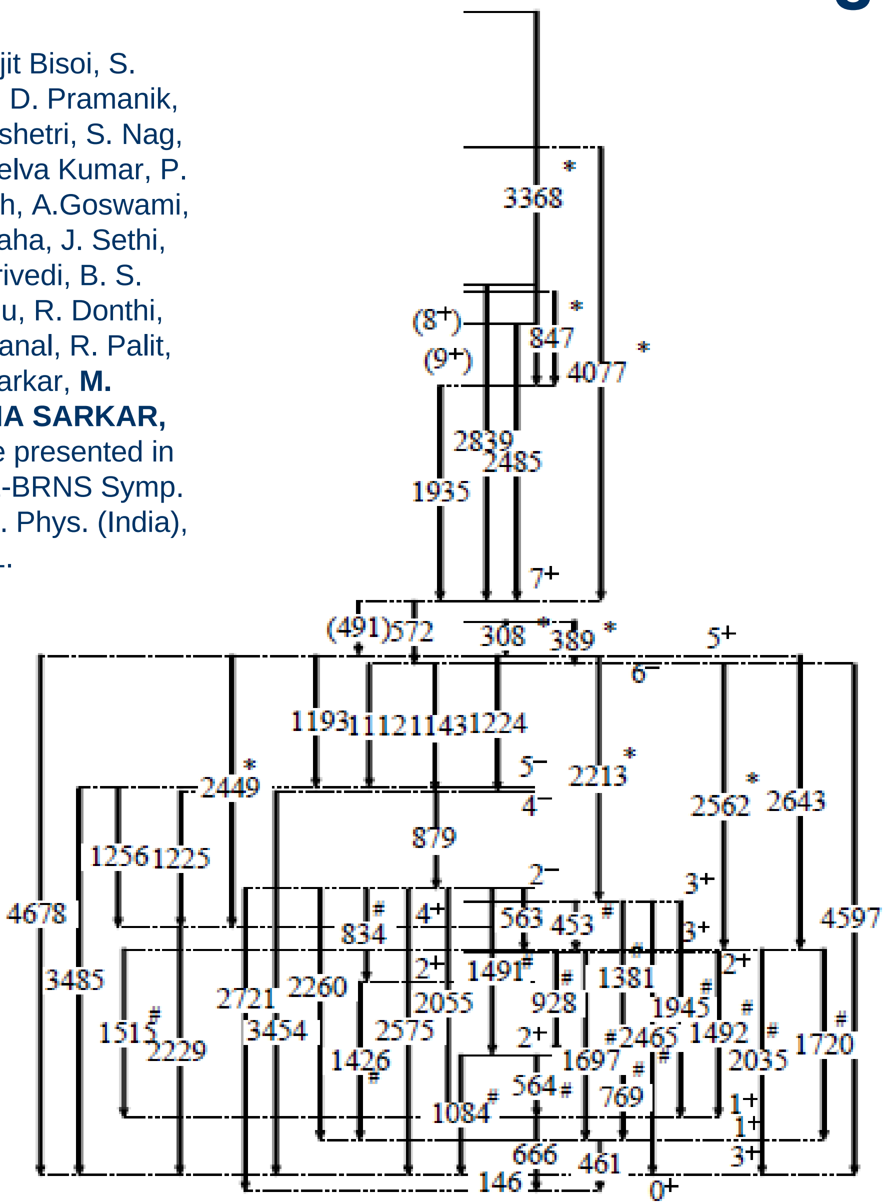
^{37}Ar

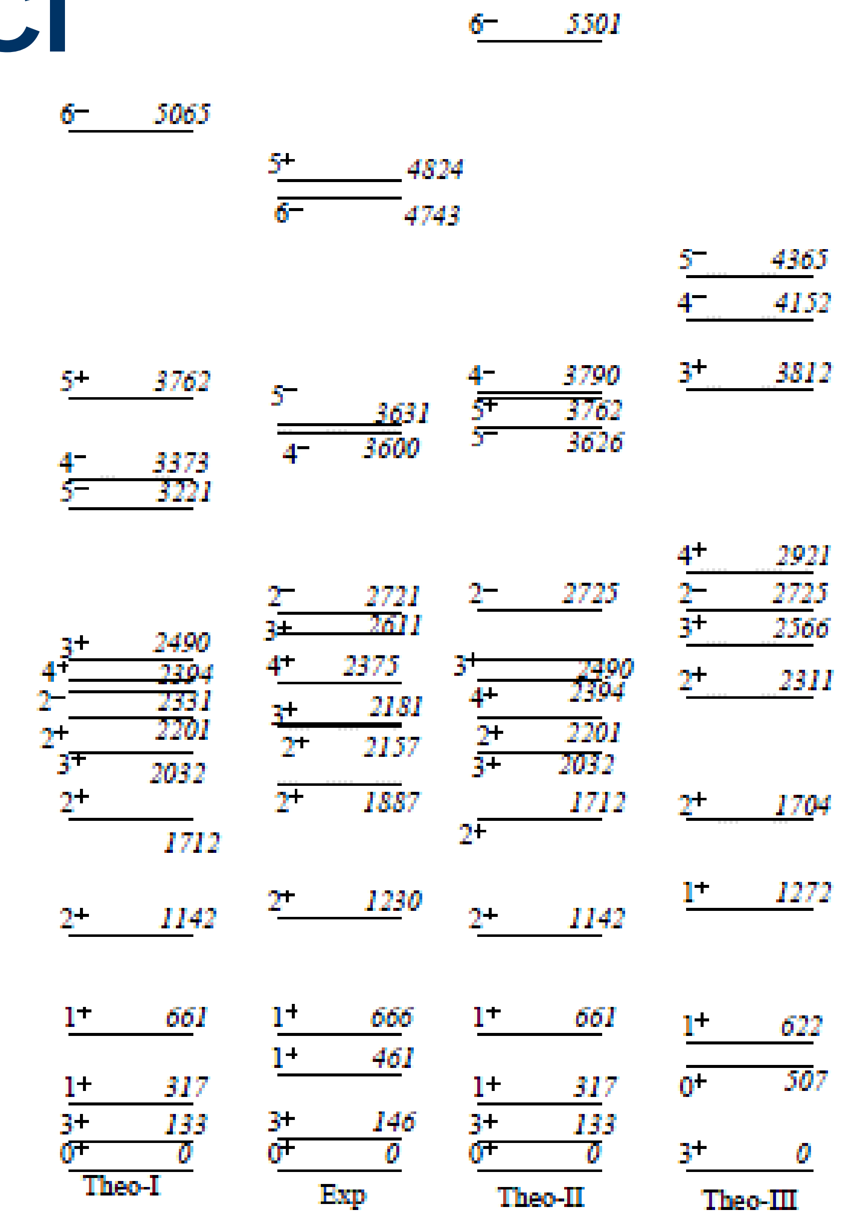
Sudatta Ray, I. Ray, Ritesh Kshetri, R. Raut, S. Ganguly, M. K. Pradhan, D. Kanjilal, M. Ray Basu, A. Chakraborty, Krishichayan, A. Mukherjee, G. Ganguly, S.S. Ghugre, S. Bhattacharya, P. Banerjee, A. Goswami, A. Deo, S.Kumar, H. C. Jain, I.Mazumdar, R.Palit, S. Sarkar, **M. SAHA SARKAR,** Proc. DAE-BRNS Symp. Nucl. Phys. (India) 53 (2008) 353.

Manuscript under preparation

^{34}Cl

Abhijit Bisoi, S. Ray, D. Pramanik, R. Kshetri, S. Nag, K. Selva Kumar, P. Singh, A.Goswami, S. Saha, J. Sethi, T. Trivedi, B. S. Naidu, R. Donthi, V. Nanal, R. Palit, S. Sarkar, **M. SAHA SARKAR,** to be presented in DAE-BRNS Symp. Nucl. Phys. (India), 2011.



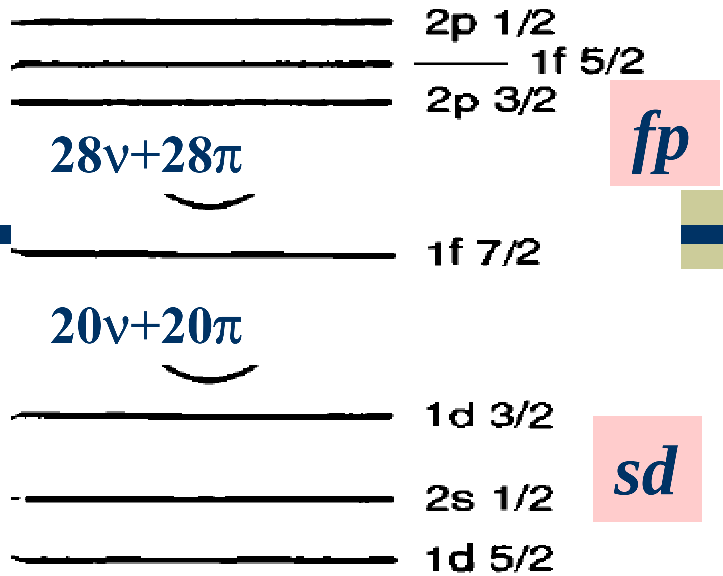


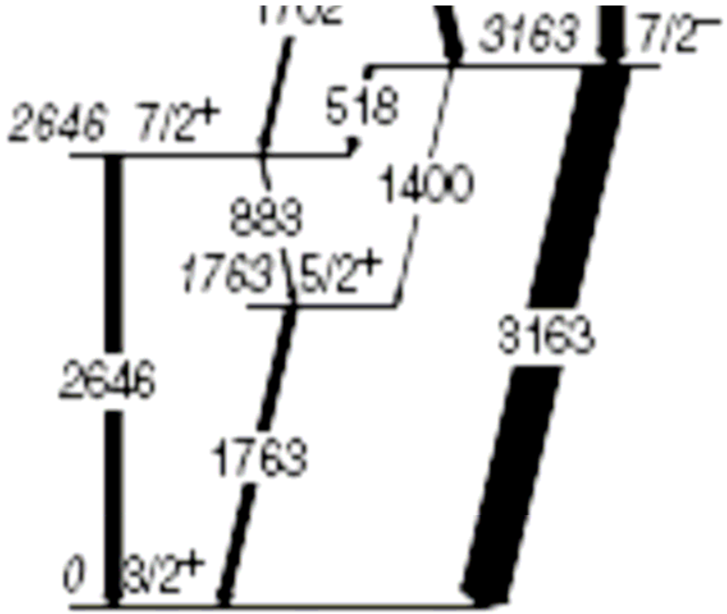
Salient features in the excitation spectrum of ^{35}Cl

^{35}Cl (Z=17, N=18), with ^{16}O core
Valence protons: 9 valence neutrons: 10

We found lowest positive parity state at 1763 keV and most intense gamma from the lowest negative parity state at 3163 keV.

So inclusion of a negative parity orbital in the valence space is essential to explain the low energy spectrum also.



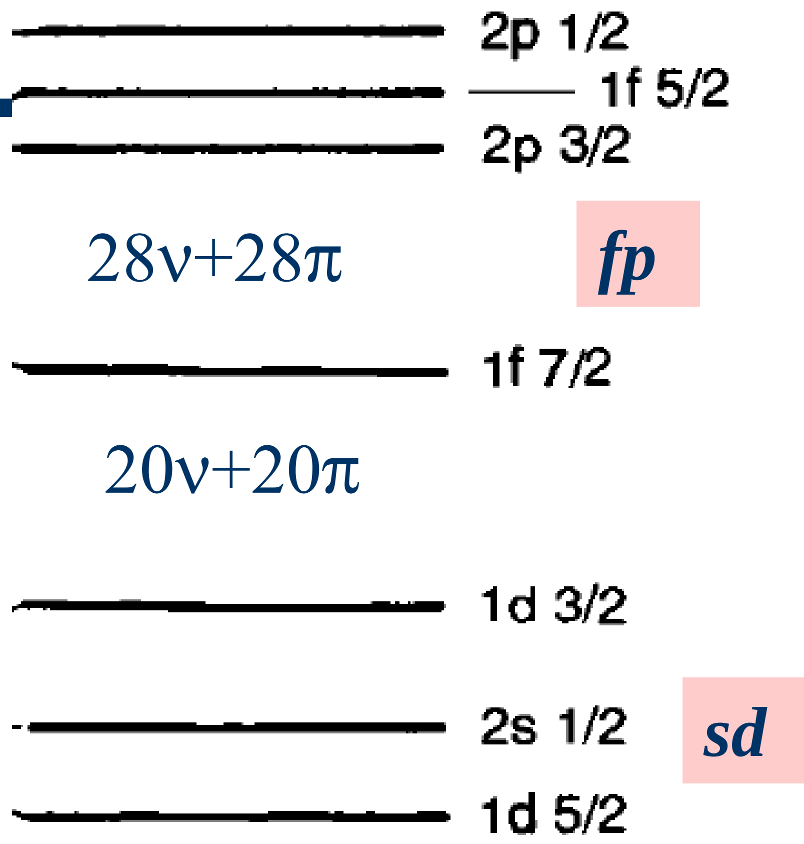


Shell Model studies

In the shell model calculations of these nuclei, in particular for the negative parity states (even for the positive parity states of relatively higher spins), one needs a nuclear Hamiltonian over the ***sd* − *fp*** valence space.

The Hamiltonian thus consists of three parts, viz., *sd*- and *fp*-shell interactions and the cross-shell ones.

It consists of Wildenthal's matrix elements for the ***sd*** shell, Mcgrory's Hamiltonian for ***fp*** shell and modification of the Millner–Kurath interaction for the cross-shell components.



Nucl. Phys. A 781 (2007) 277.

Limitations

•For the positive parity states, 0 ħω excitation has been considered, i.e only the full *sd* shell has been used as the valence space.

Nucl. Phys. A 781 (2007) 277.

• Low energy spectra reproduced quite accurately.

•But the energies for higher spin positive parity states beyond $9/2^+_1$ are predicted substantially higher than the experimental ones - insufficiency of the valence space. The nucleon excitations to the neighbouring *fp* shell are therefore essential.

• Simplest way to get negative parity states: through 1 ħω excitation, i.e. only 1*p*–1*h*, *sd* → *fp* excitations are allowed.

• The calculated energies of the negative parity levels are consistently higher compared to the experimental values

This was also observed by previous workers (A. Kangasmaki et al. Phys. Rev. C 58 (1998) 699; A. Kangasmaki et al., Phys. Rev. C 55 (1997) 1697;P. Mason, et al., Phys. Rev. C 71 (2005) 014316; M. Ionescu-Bujor, et al., Phys. Rev. C 73 (2006) 024310 ………………) where the predictions for negative parity states with accuracy better than 500−600 keV were found to be difficult.

This was attributed to the overestimation of the *sd*–*fp* gap in the corresponding interaction.

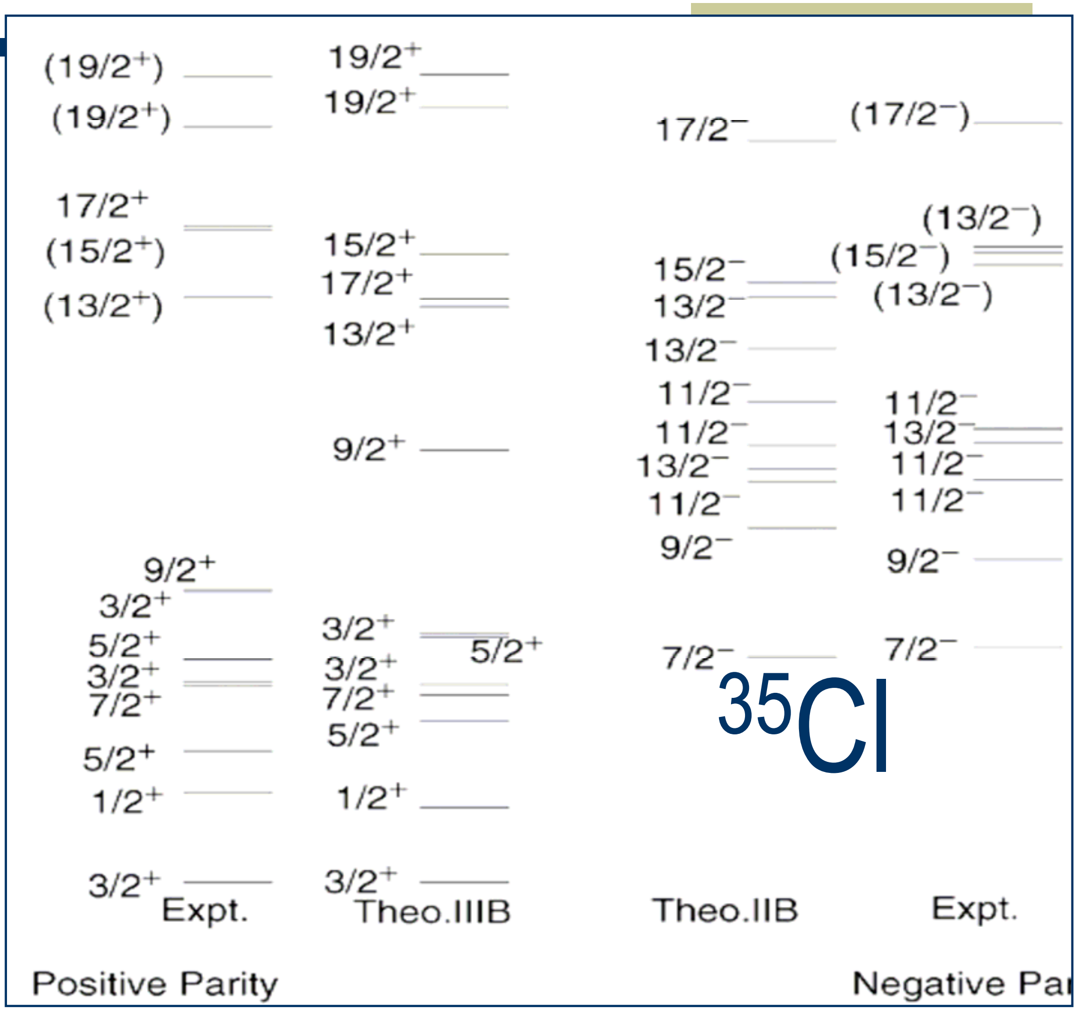
The nuclei near stability and the *sd-fp* shell gap

To improve the agreement for the negative parity states and high spin positive parities, we have depressed the single particle energies (SPES) of $1f_{7/2}$ and $2p_{3/2}$ so that the first negative party state is reproduced.

Dramatic improvement of results indicate :

- excitations to ***fp*** shell essential to reproduce even the positive parity higher spin states.
- The ***sd–fp*** shell gap has to be decreased to reproduce both positive and negative parity levels.

R. Kshetri et al. Nucl. Phys. A 781 (2007) 277.



Similar observation for ^{30}P, ^{36}Cl, ^{37}Ar ...

Approaching the “island of inversion”: ^{34}P
P. C. Bender et al., PHYSICAL REVIEW C 80, 014302 (2009)

Cross-shell excitations in ^{30}Al and ^{30}Si at high spin
D. Steppenbeck et al., Nuclear Physics A 847 (2010) 149–167

The recently-developed WBP-a Hamiltonian was also used to calculate the negative-parity states by allowing 1p–1h excitations within a model space incorporating the ***sd*** shell with the 0***f***7/2 and 1***p***3/2 orbitals. In this modified interaction, the energies of the two ***fp***-shell orbits were reduced by 1.8 and 0.5 MeV to better reproduce level energies in neutron-rich phosphorous isotopes.

Recently,

High-spin structure of ^{37}Cl, intruder excitations, and the ***sd-fp*** shell gap by M. Ionescu-Bujor et al. PHYSICAL REVIEW C 80, 034314 (2009)

indicated that the shell gap between the *sd* and *fp* shells produced by the

•*sdfp* interaction is somewhat underestimated, need for increasing the sd-fp gap

,

•while this is overestimated for SDPF-M interaction. need for decreasing the sd-fp gap

The choices of single-particle energies

- The single-particle energies SPE's are determined so as (SET A) *SDPF-M*, *sdpfmw* ..
  - to reproduce the neutron separation energies and the one particle spectra of ^{17}O (***sd*** shell) and ^{41}Ca (***f p*** shell)
    - Over predicted energies of negative parity states indicating that the $d_{3/2}$-$f_{7/2}$ gap produced may be too large
  - SET A modification:
    - reduction of spes of ***fp*** orbitals improves results for high spin positive parity and low spin negative parity states dramatically.

- The *sdfp* effective interaction takes ^{28}Si as a core, and the single-particle energies (SET B) are chosen in order to reproduce the
  - single-particle states in ^{29}Si.
    - calculated energies are systematically smaller than the experimental energies indicated that the shell gap between the *sd* and *fp* shells produced by the *sdfp* interaction is somewhat underestimated,
  - SET B modification:
    - increasing the ***f***$_{7/2}$ and ***p***$_{3/2}$ single-particle energies.

•Thus the ***sd* – *fp*** shell gap appears to evolve as a function of proton number.

M. SAHA SARKAR, Proc. DAE-BRNS Symp. Nucl. Phys. (India) 55 (2010) I19 (http://www.sympnp.org/proceedings/index.php: electronic version only)

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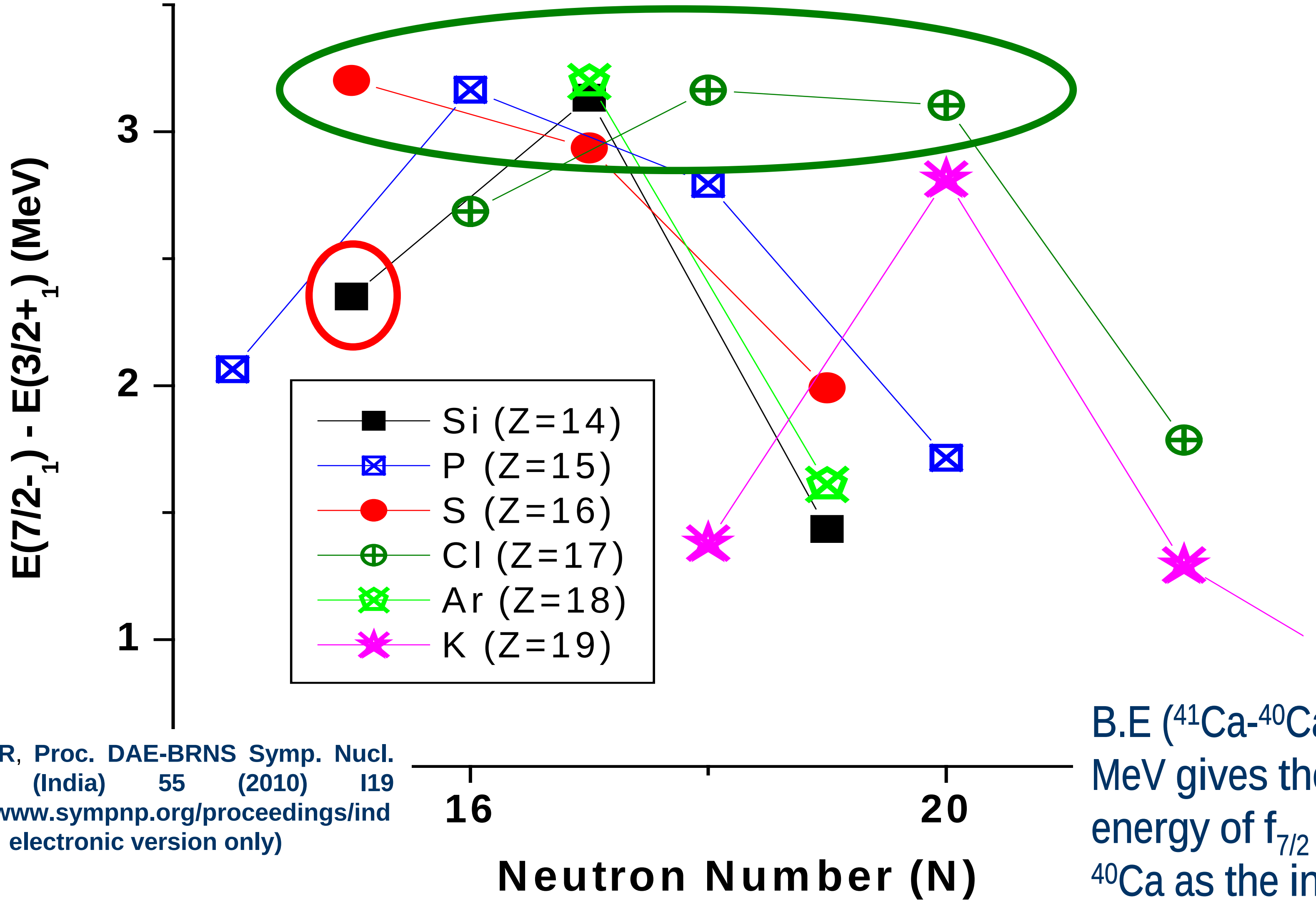
•If the intruder spes are estimated from ^{41}***Ca*** spectra with respect to ^{16}***O*** core, this gap needs to be reduced for reproduction of ^{30}***P***, ^{35,36}***Cl*** and ^{37}***Ar*** spectra. B.E (^{41}Ca-^{40}Ca) = -8.36 MeV gives the s.p. energy of $f_{7/2}$ state w.r.to ^{40}Ca as the inert core.

•On the other hand, if one takes ^{28}***Si*** as a core and chooses the spes in order to reproduce the single-particle states in ^{29}***Si***, it is found that the ***sd−fp*** gap thus obtained needs a small increase to reproduce the experimental data for ^{37}***Cl***.

•Thus the ***sd − fp*** shell gap appears to evolve as a function of proton number.

•An alternative solution could be to change the matrix elements of the effective interaction that connect the ***sd*** with the ***fp*** shell. Usually the single-particle energies (spes) used in these Hamiltonians are devoid of the influence of the cross-shell interactions and have to be re-adjusted to reproduce the observed energy spectra. Computational limitations due to large dimensionality problem lead to the truncation of the model space. This may also require an readjustment of the spes.

•This may have direct relevance to the island inversion observed for neutron rich isotopes in this mass region.



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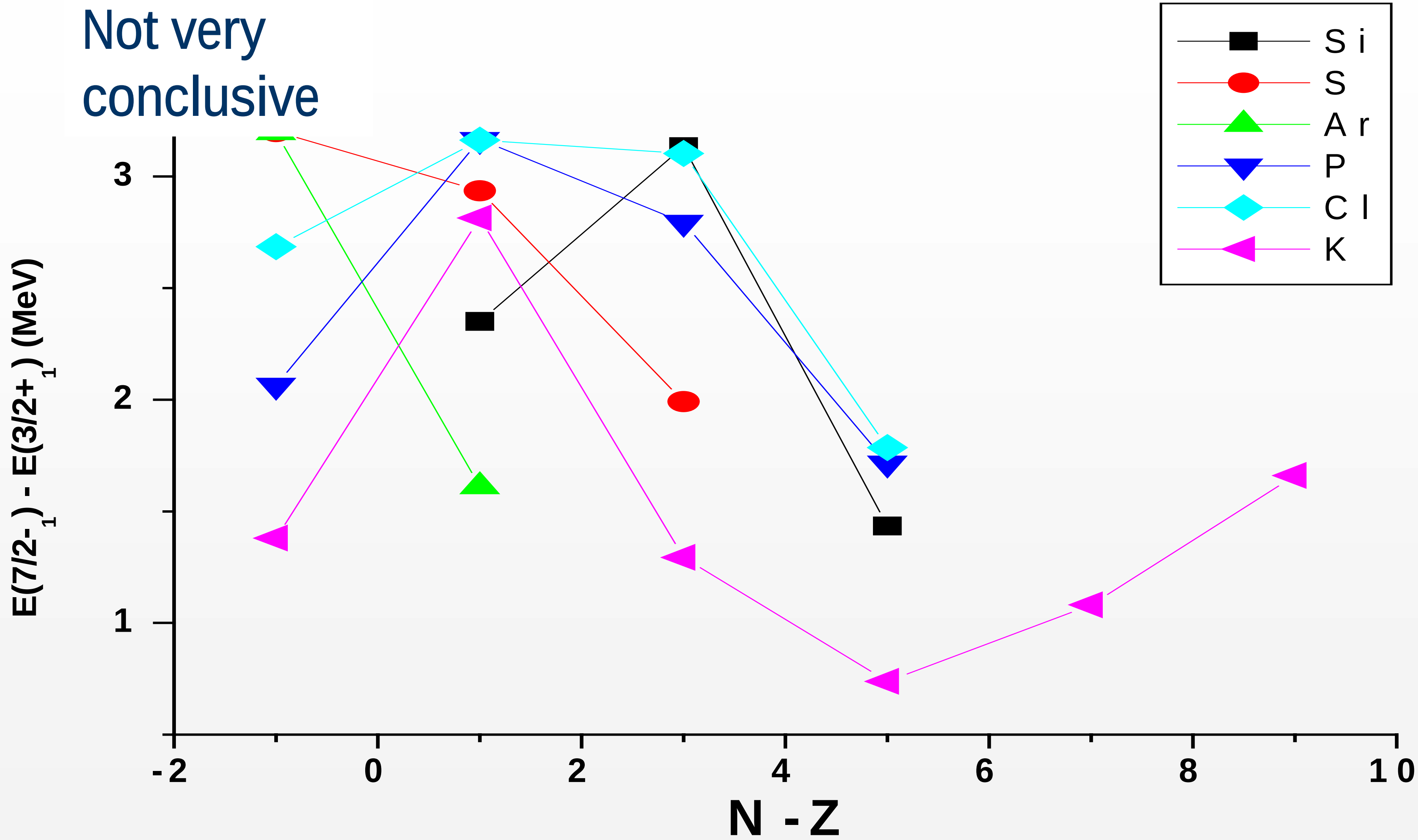
B.E (^{41}Ca-^{40}Ca) = -8.36 MeV gives the s.p. energy of $f_{7/2}$ state w.r.to ^{40}Ca as the inert core.

The curves are labeled by the j^p values of the states of the odd-A nuclei and not by the quantum numbers (nlj) of the expected single-particle orbits. This choice is governed by the fact that the spectroscopic factor of the first j state does not always exhaust the sum rule arising from the j orbit. *O. Sorlin, M. G. Porquet / Progress in Particle and Nuclear Physics 61 (2008) 602–673.*

Note that the state may arise from a neutron/ proton intruder orbital – working in JT space

Not very conclusive

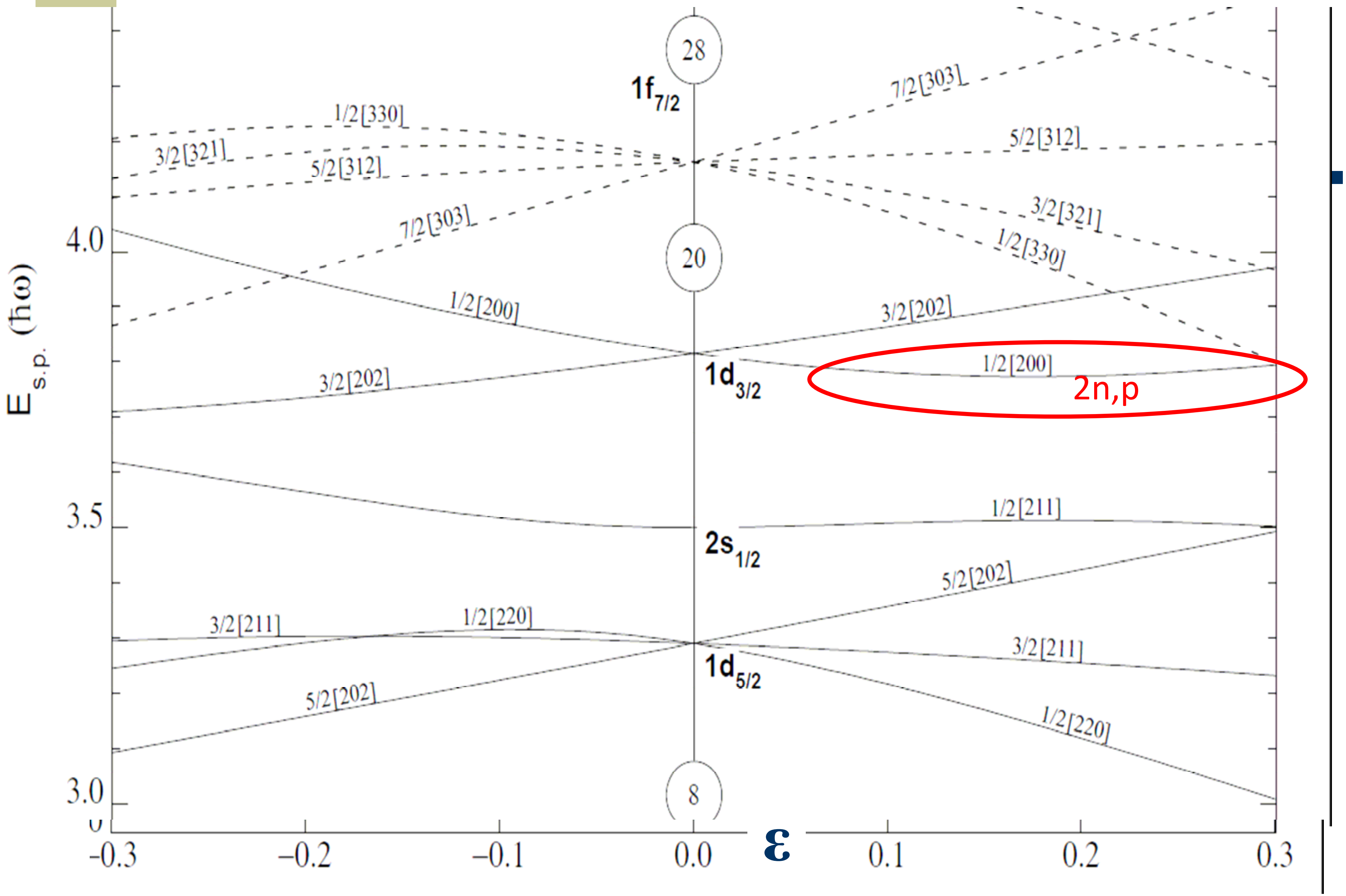


suggestion that the position of the intruder state is dependent almost entirely on *N-Z*. PHYSICAL REVIEW C 77, 034305 (2008)

M. SAHA SARKAR, Proc. DAE-BRNS Symp. Nucl. Phys. (India) 55 (2010) I19 (http://www.sympnp.org/proceedings/index.php: electronic version only)

The nuclei in the neighborhood of doubly closed ^{40}Ca usually exhibit characteristics of single particle excitation. This feature is suitable for applications of spherical shell model calculation in the sd shell.

The spectroscopy of several nuclei in the mass region revealed deformed states (even Superdeformation) at low excitation energies, indicating that the nuclei near the closed shell with Z=20 can easily lose spherical shape.

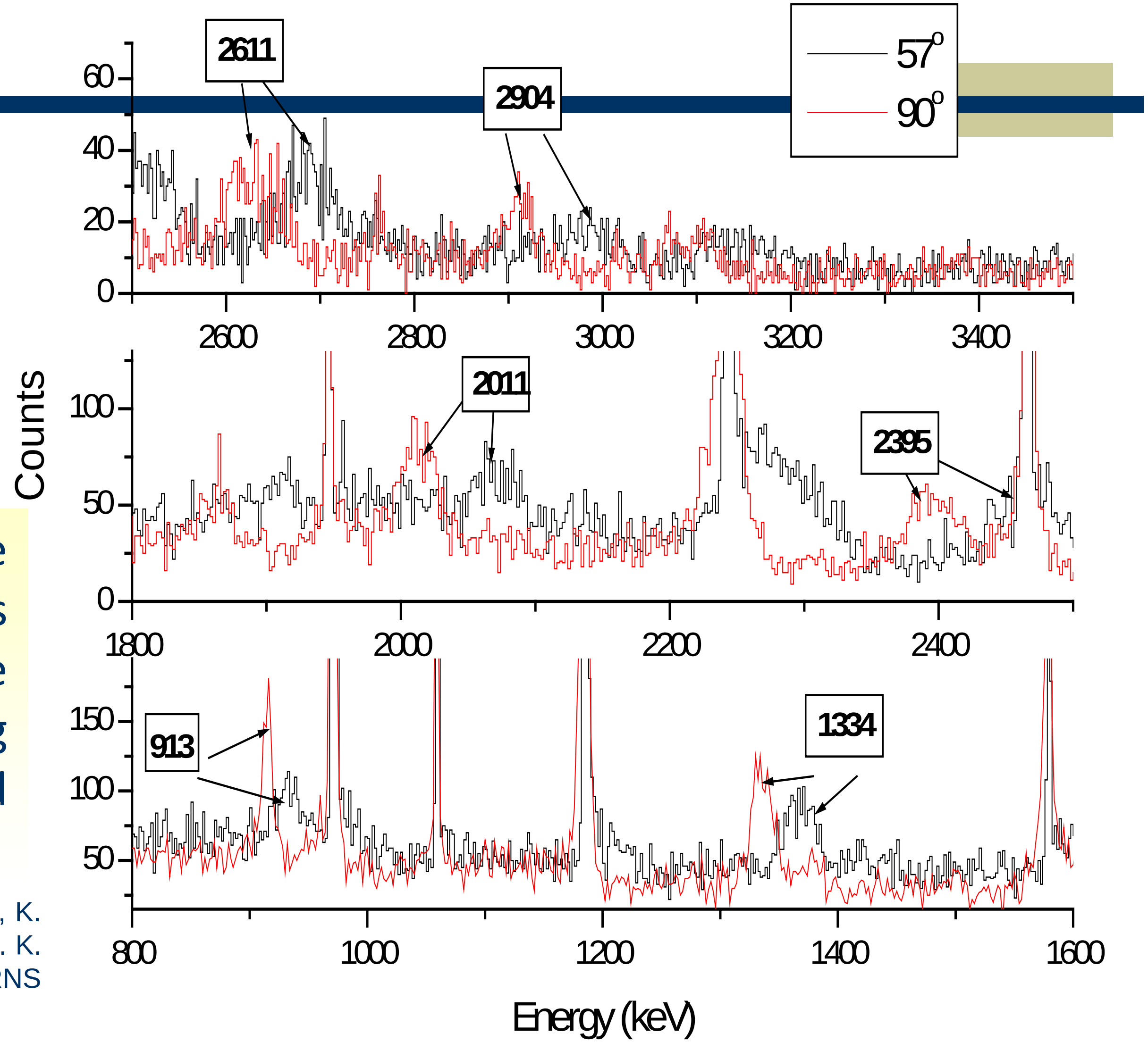


28
20
8
1f7/2
1d3/2
2s1/2
1d5/2
1/2[330]
3/2[321]
5/2[312]
7/2[303]
1/2[200]
3/2[202]
1/2[211]
5/2[202]
3/2[211]
1/2[220]
2n,p
4.0
3.5
3.0
Es.p. (ħω)
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
ε

Indication of deformation in ^{35}Cl

$^{28}Si(^{12}C,p\alpha)^{35}Cl$ experimental spectra from different detectors angle generated by putting gates on the 3163 keV transition in ^{35}Cl show the six shifted peaks from around 900 keV to 3000keV.

The lifetimes of the corresponding states must be shorter than the characteristic stopping time of ^{35}Cl recoils in gold (Au) backing.



Abhijit Bisoi, S. Ray, M. Roy Basu, D. Kanjilal, Somnath Nag, K. Selva Kumar, A. Goswami, N. Madhavan, S. Muralithar, R. K. Bhowmik, S. Sarkar, **M. SAHA SARKAR**, Proc. DAE-BRNS Symp. Nucl. Phys. (India) 55 (2010) 4.

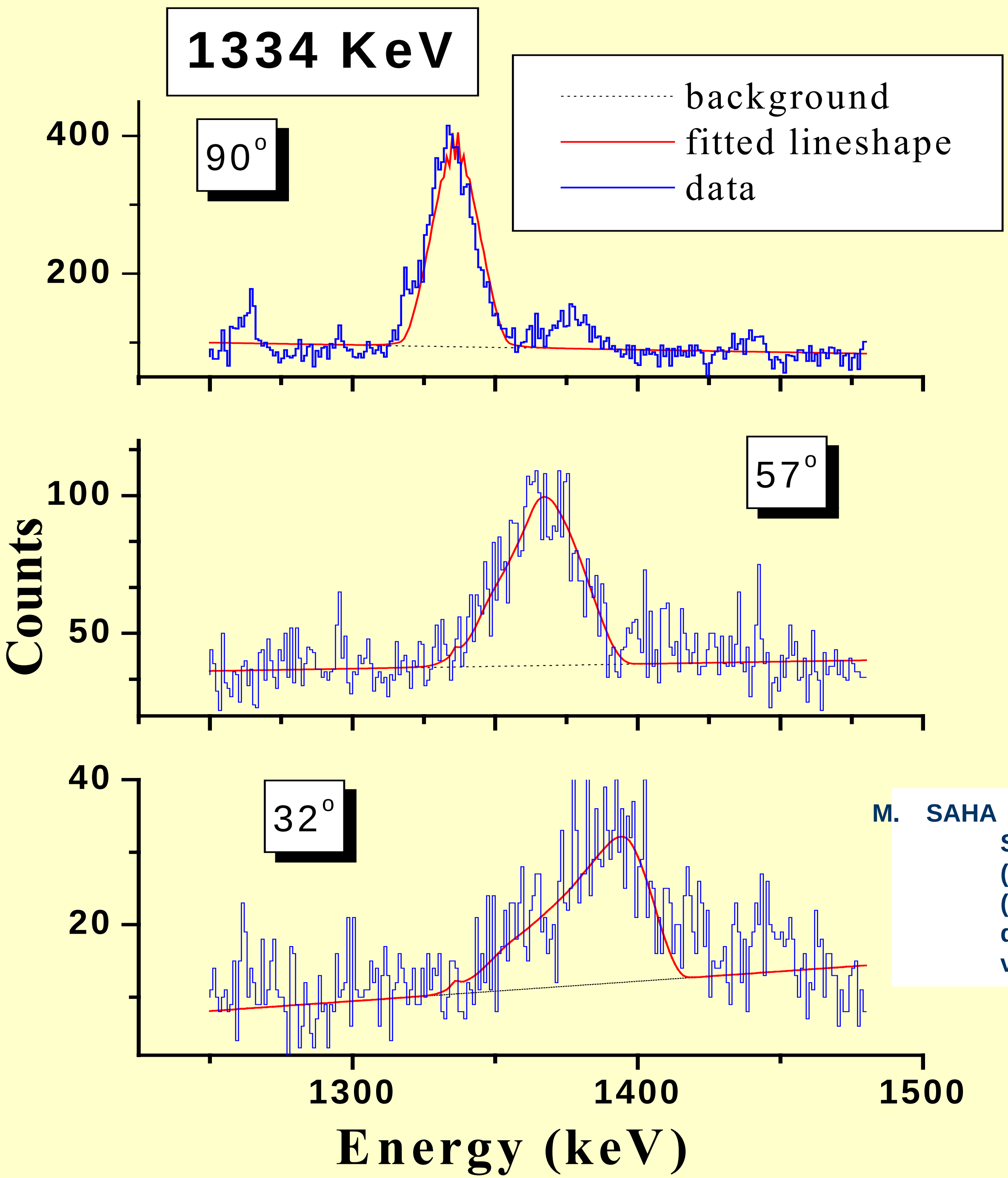
Do they form a deformed band?

They belong to a single band.

They have E(2) multipolarity.

Abhijit Bisoi, S. Ray, M. Roy Basu, D. Kanjilal, Somnath Nag, K. Selva Kumar, A. Goswami, N. Madhavan, S. Muralithar, R. K. Bhowmik, S. Sarkar, **M. SAHA SARKAR**, Proc. DAE-BRNS Symp. Nucl. Phys. (India) 55 (2010) 4.

Having very short life time due to large quadrupole moments.



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Theory (Particle Rotor Model)

Theoretical calculations using a version of the Particle-Rotor Model (PRM), where experimental energies of the core can be directly given as inputs, have been done.

- The SD band of ^{36}**Ar** are used as **core energies**.
- $^{35}_{17}\mathrm{Cl}_{18} \Rightarrow {}^{36}_{18}\mathrm{Ar}_{18}$ **+ 1 proton hole**

- $^{35}_{17}\mathrm{Cl}_{18}$ with 17 protons – π Fermi level lies near the
  - low Ω orbitals of $f_{7/2}$ for the prolate option

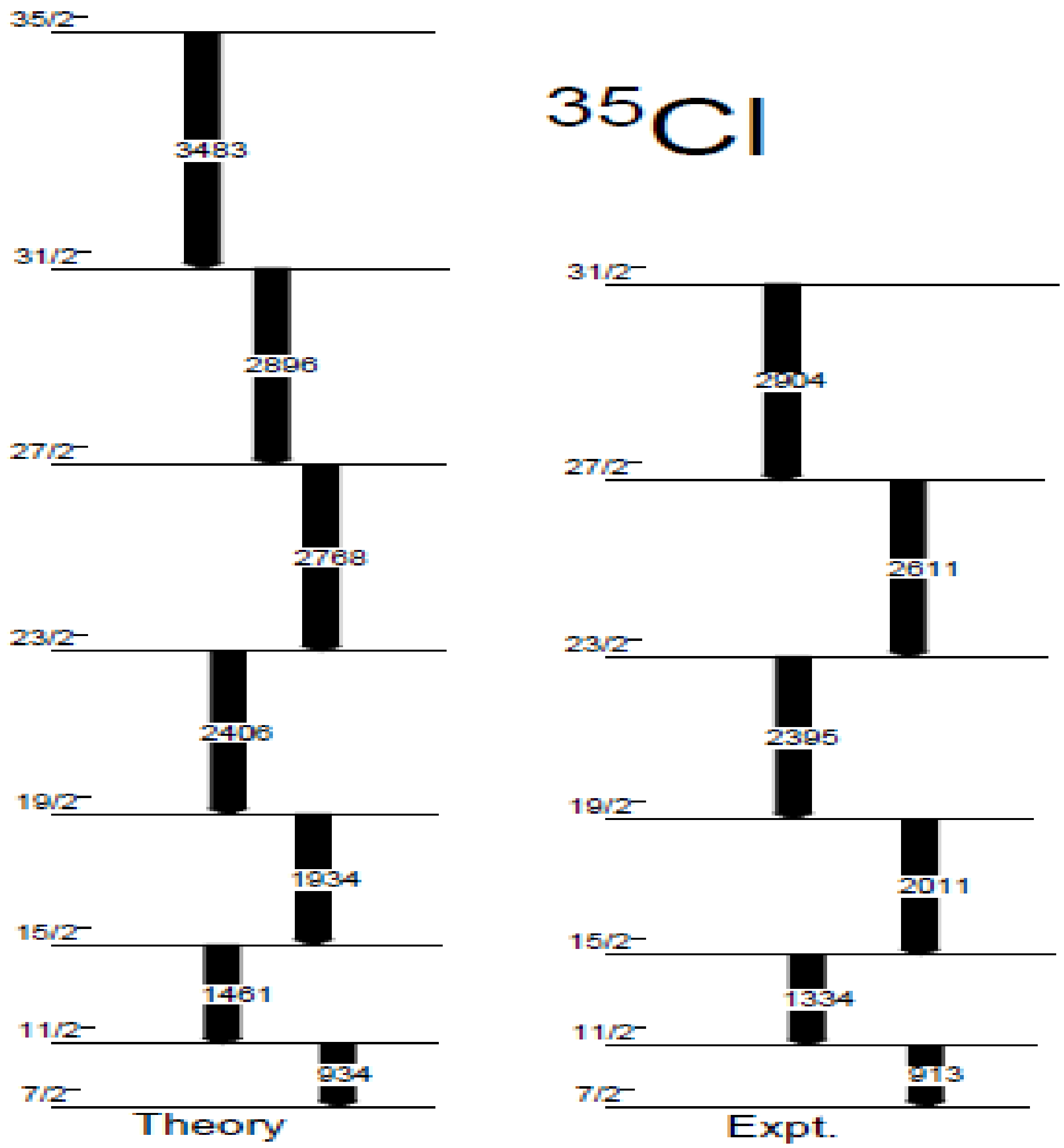
  λ = 48.0 MeV, Δ = 1.7 MeV

- ✓ μ =0.520, κ = 0.073, δ = 0. 45,
  - Attenuation coefficient = 1.00

Abhijit Bisoi, S. Ray, M. Roy Basu, D. Kanjilal, Somnath Nag, K. Selva Kumar, A. Goswami, N. Madhavan, S. Muralithar, R. K. Bhowmik, S. Sarkar, **M. SAHA SARKAR**, Proc. DAE-BRNS Symp. Nucl. Phys. (India) 55 (2010) 4.

➢**Particle-rotor model calculations of superdeformed bands in A=150 and 190 regions**, M. Saha Sarkar, Phys. Rev. C 60, 064309 (1999).

Level structure of ^{35}Cl:



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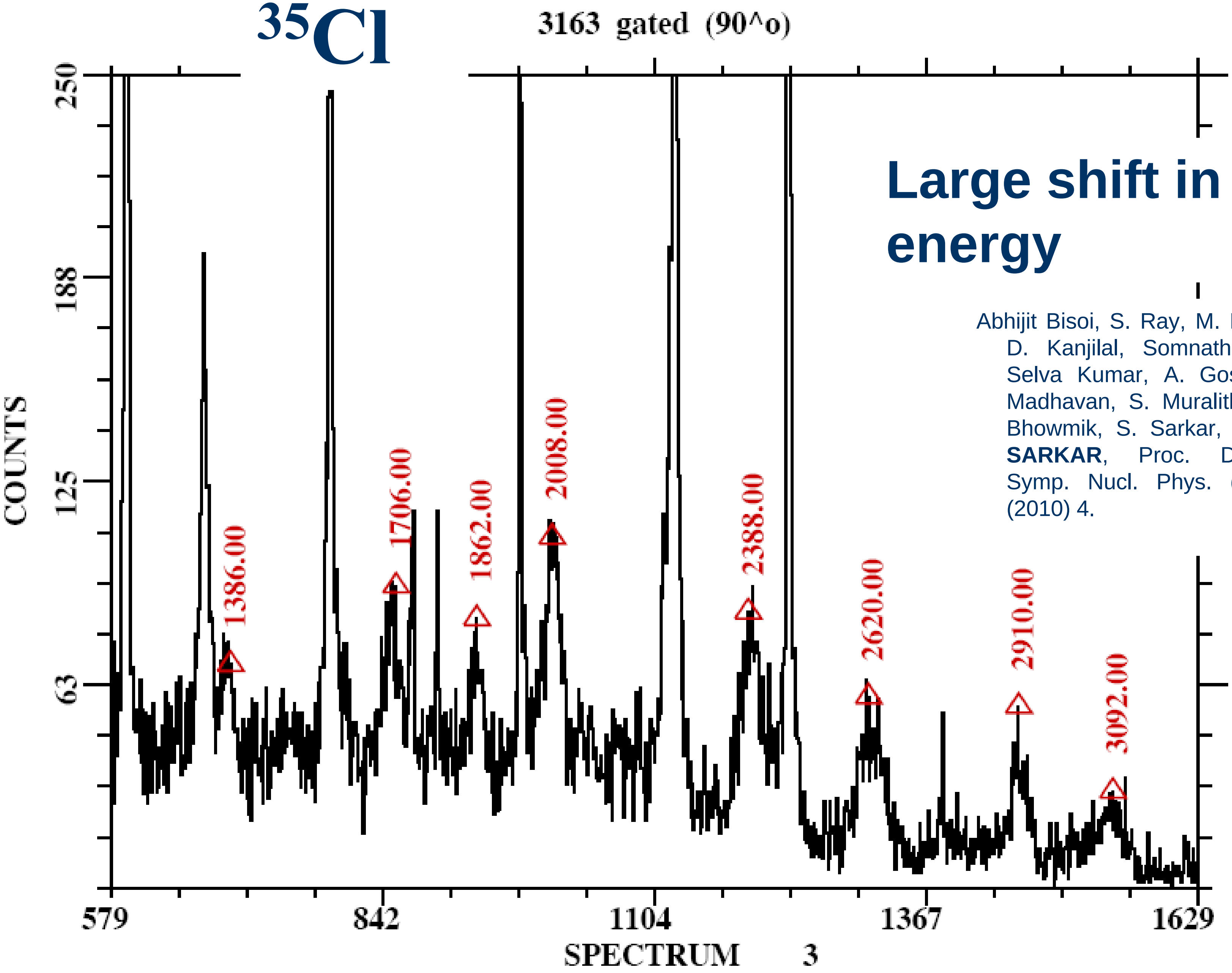
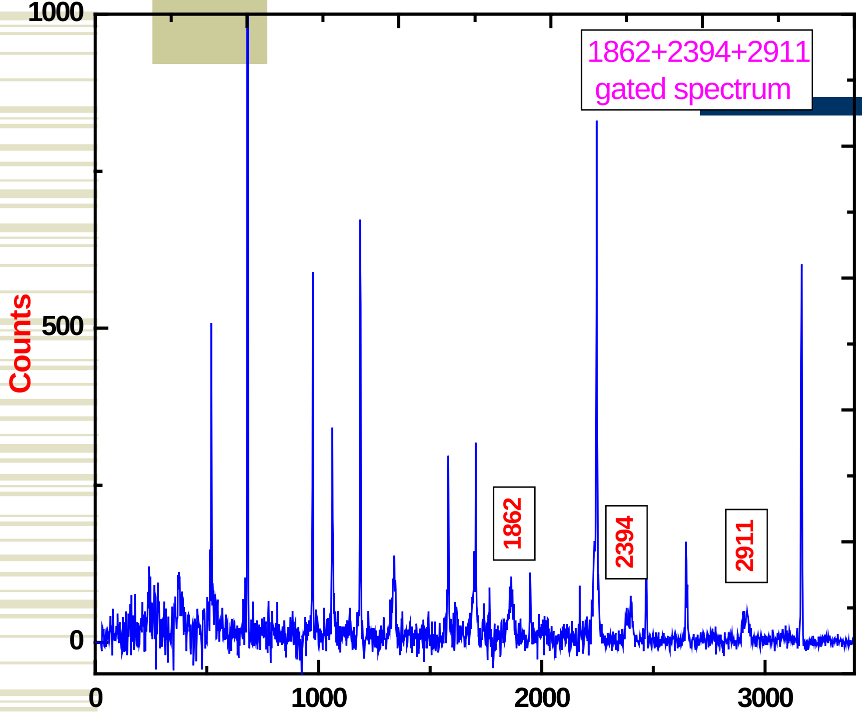
^{35}Cl

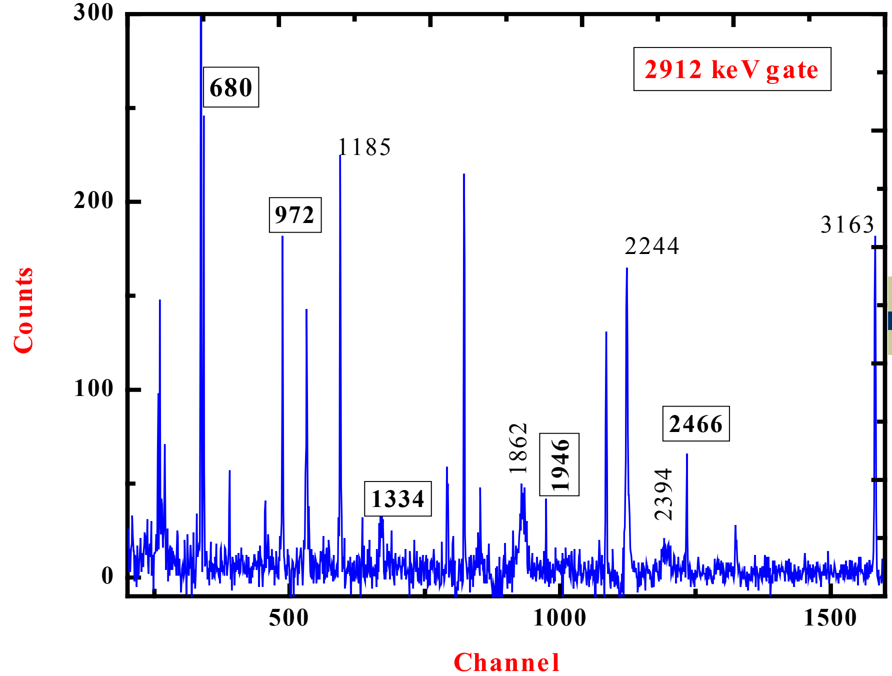


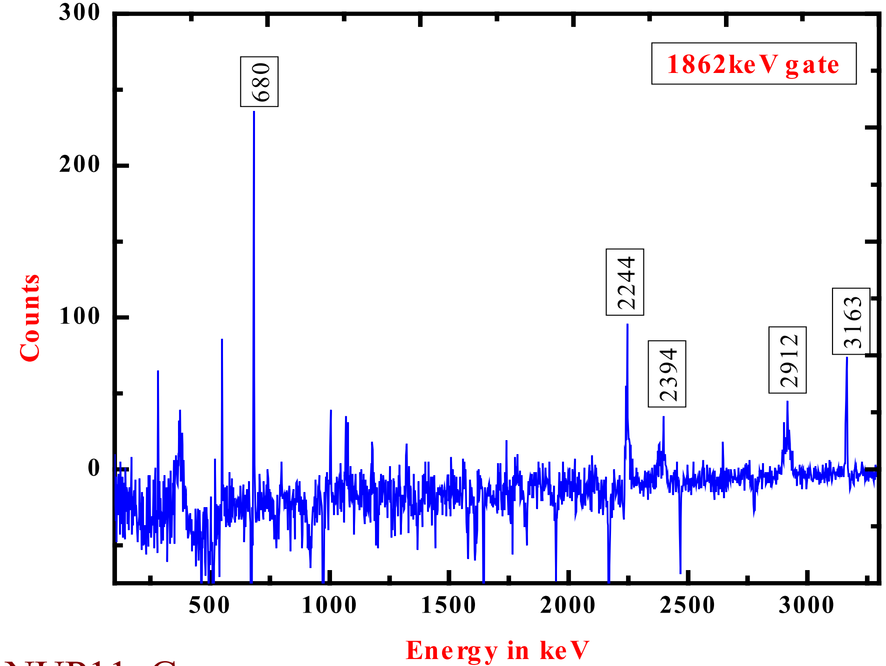
Large shift in energy

Abhijit Bisoi, S. Ray, M. Roy Basu, D. Kanjilal, Somnath Nag, K. Selva Kumar, A. Goswami, N. Madhavan, S. Muralithar, R. K. Bhowmik, S. Sarkar, **M. SAHA SARKAR**, Proc. DAE-BRNS Symp. Nucl. Phys. (India) 55 (2010) 4.

^{35}Cl

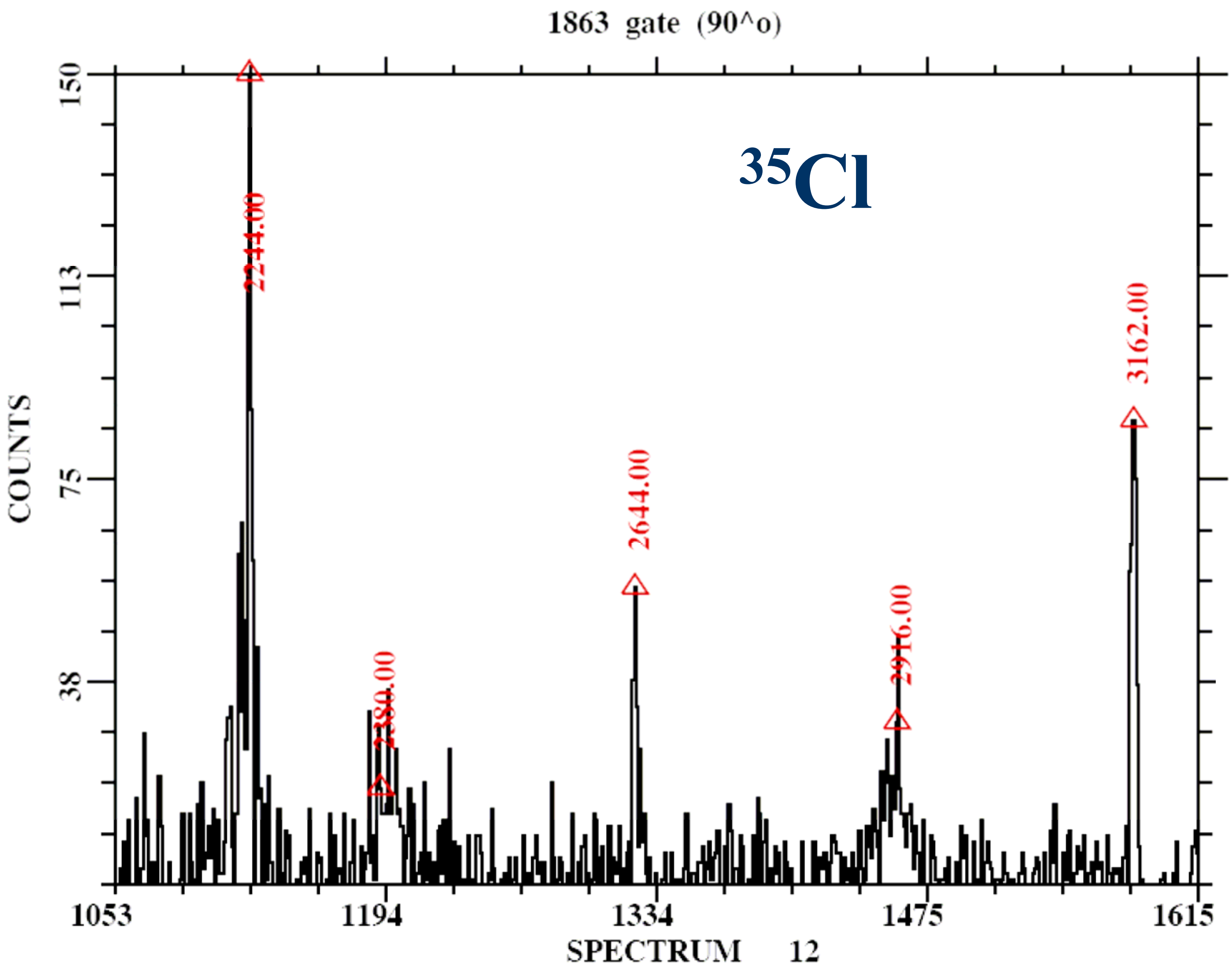






Analysis using 90º-90º matrices

Abhijit Bisoi, S. Ray, M. Roy Basu, D. Kanjilal, Somnath Nag, K. Selva Kumar, A. Goswami, N. Madhavan, S. Muralithar, R. K. Bhowmik, S. Sarkar, **M. SAHA SARKAR**,
Manuscript under preparation



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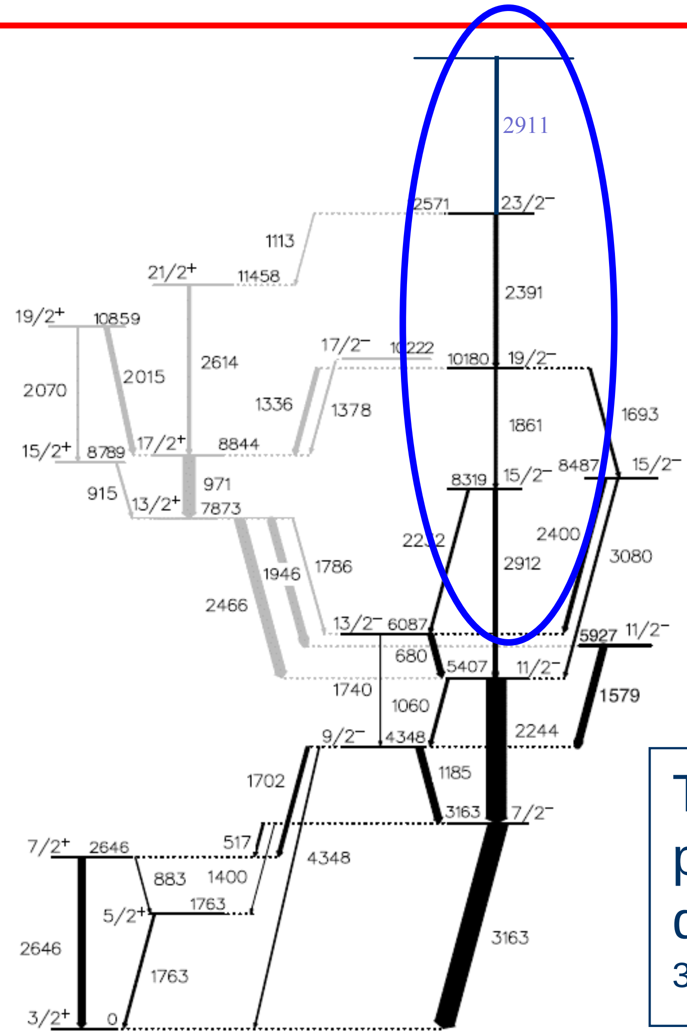

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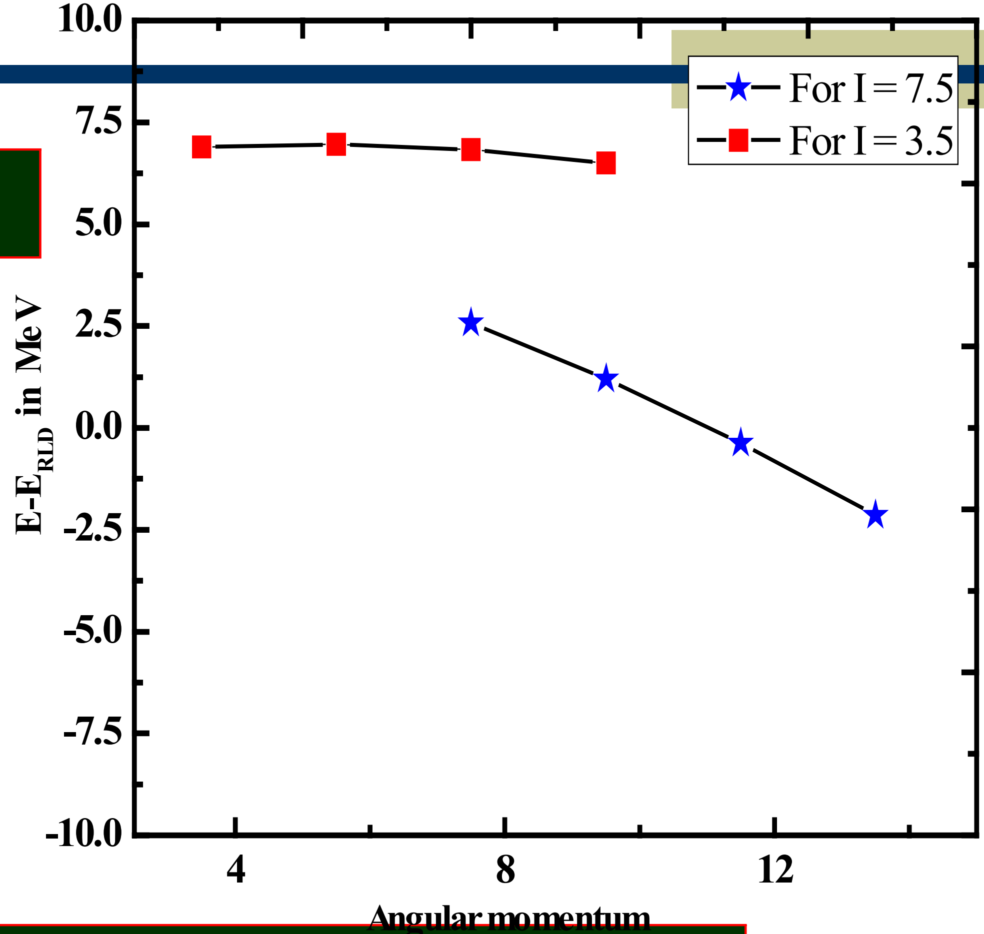
Tentative placement of the deformed band in ^{35}Cl

Excitation energy (E) relative to a rigid rotor energy E_{RLD}

$J_{rigid} = 2/5\ M R_{av}^2 [1 + 0.31\ \beta_2]$

For ^{35}Cl $E_{RLD} = 0.09004\ I(I+1)$.

$J_{rigid} > J > J_{fluid}$



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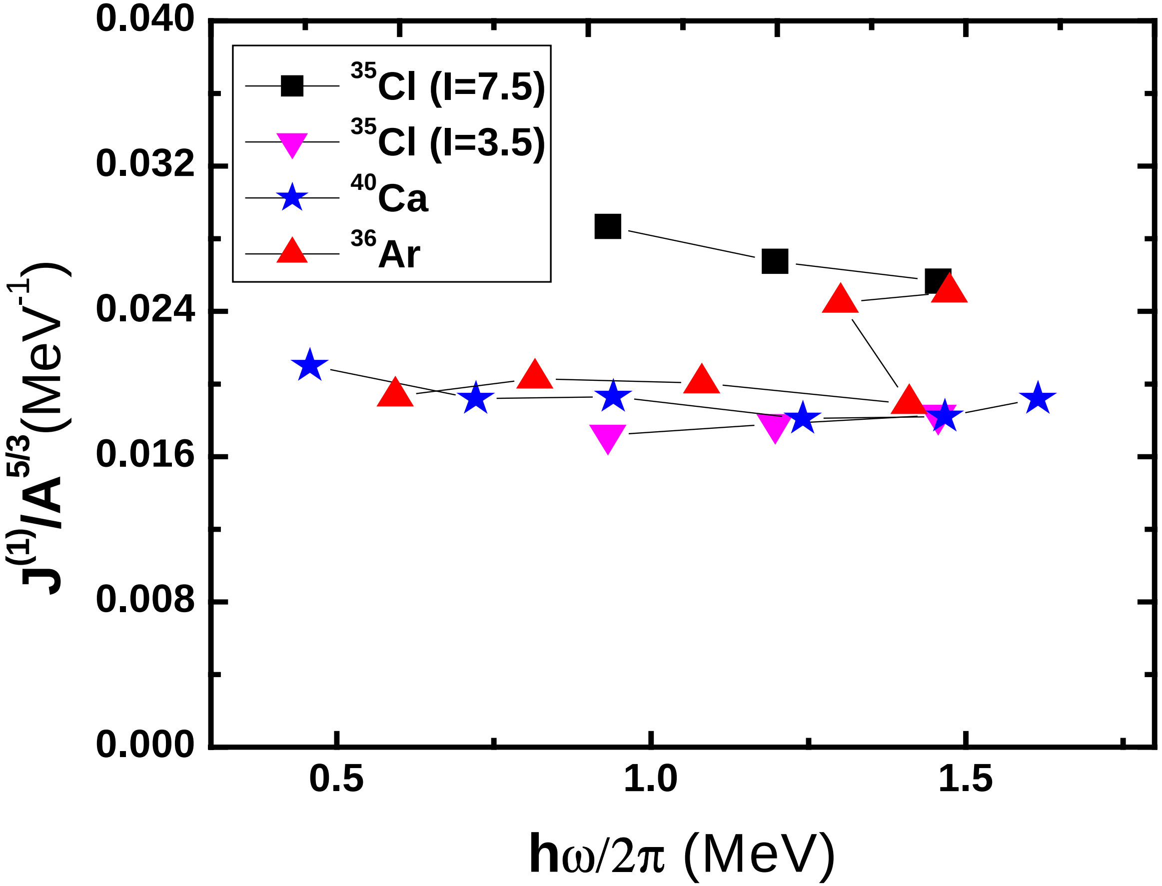
Excitation energy (E) relative to a rigid rotor energy $E_{RLD} = 0.09004\ I(I+1)$, as a function of spin.

Variation of Moments of Inertia

$J^{(1)} = \hbar^2(2I+1) / E\gamma$



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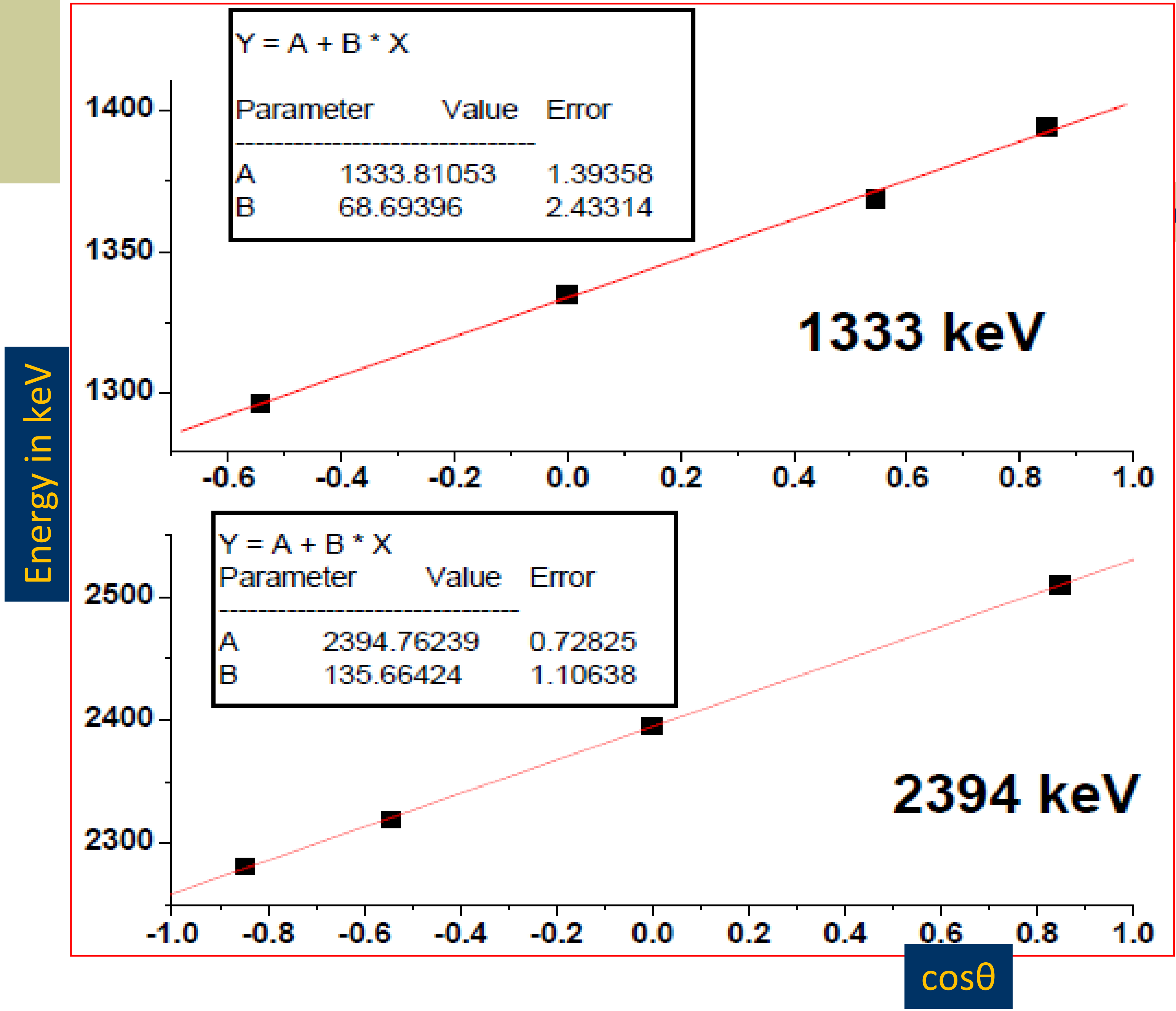
$J^{(1)}$ moments of inertia scaled by $A^{5/3}$ as a function of rotational frequency.



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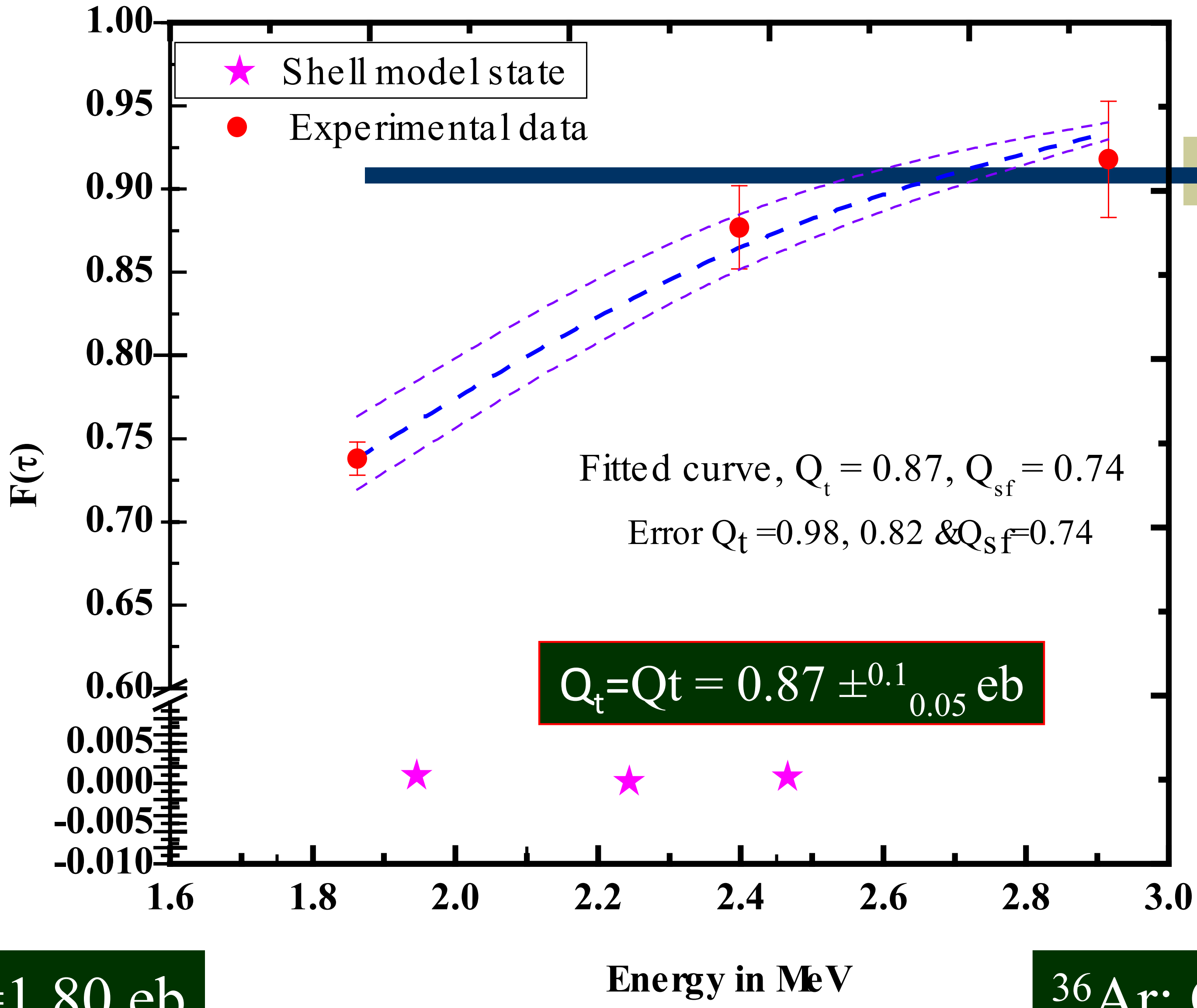
Deformed states in ^{35}Cl



Q_t=Qt = 0.87 $\pm^{0.1}_{0.05}$ eb

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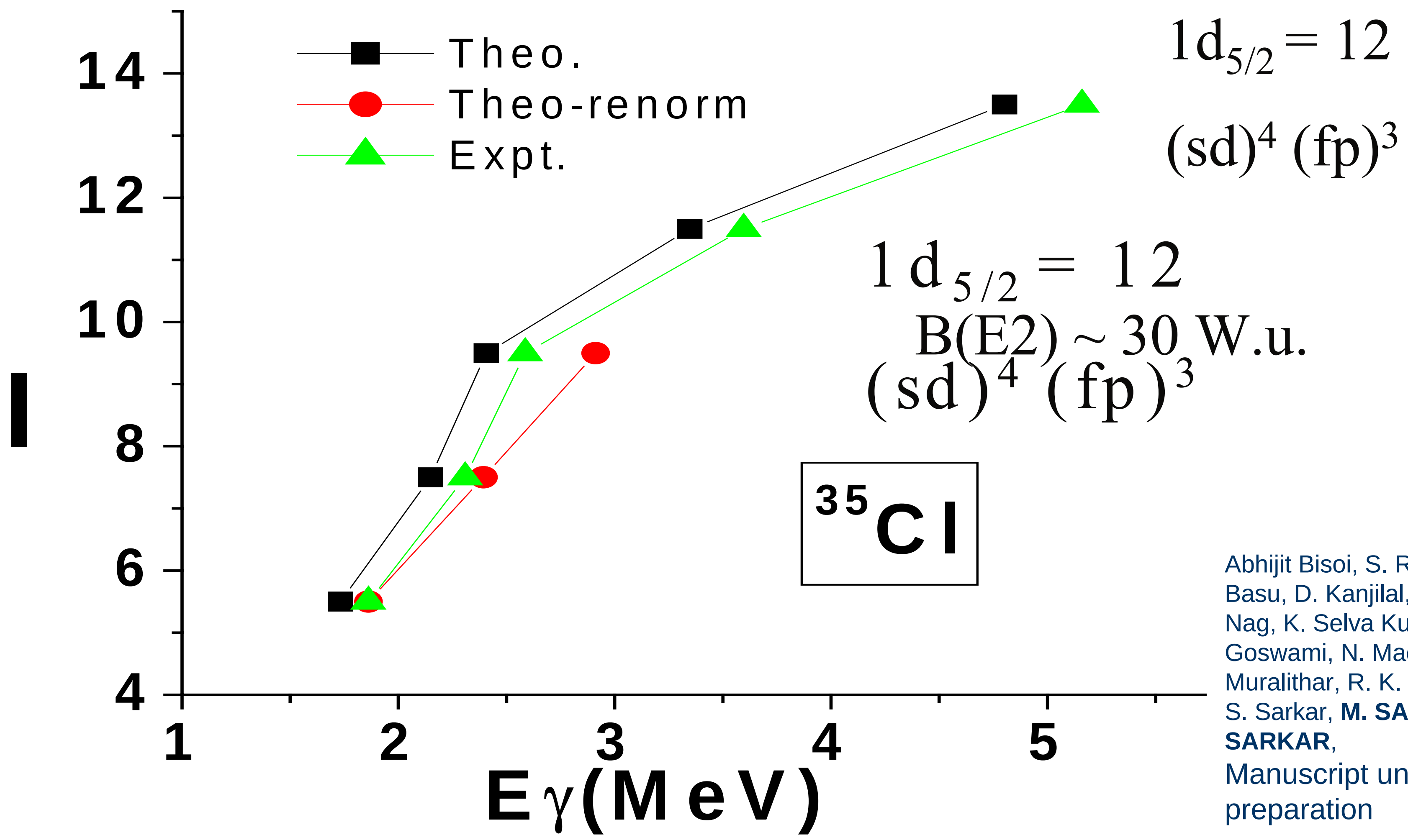
^{40}Ca: Q_t=1.80 eb

^{36}Ar: Q_t=1.18 eb

Shell Model studies



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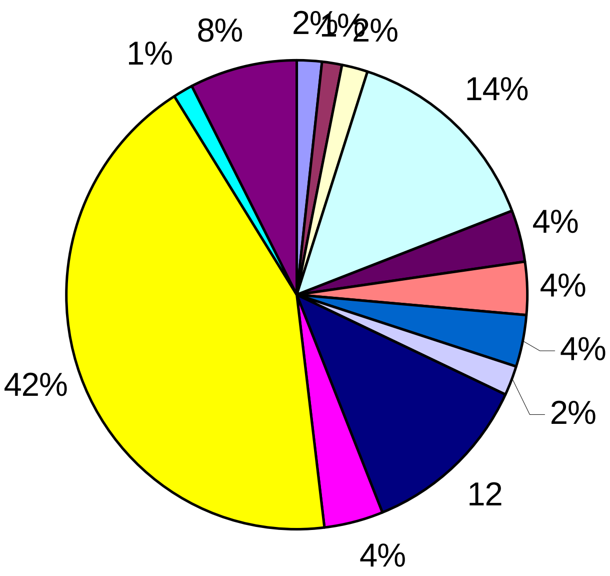
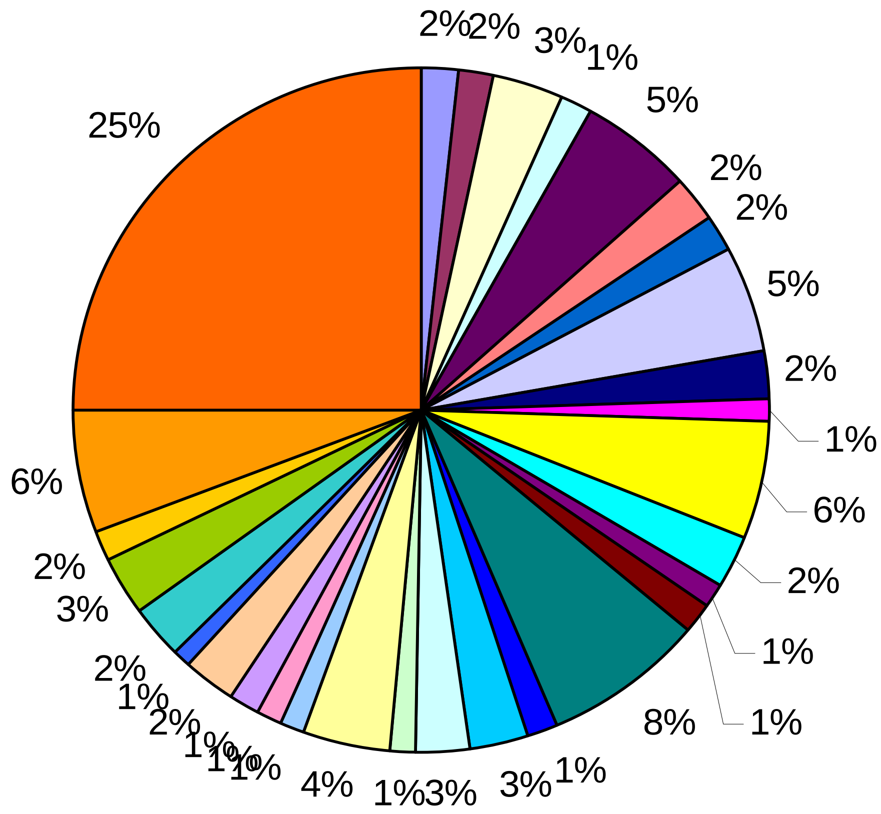
Wavefunctions

7/2⁻
(fp-1)



7/2⁻
(fp-3)



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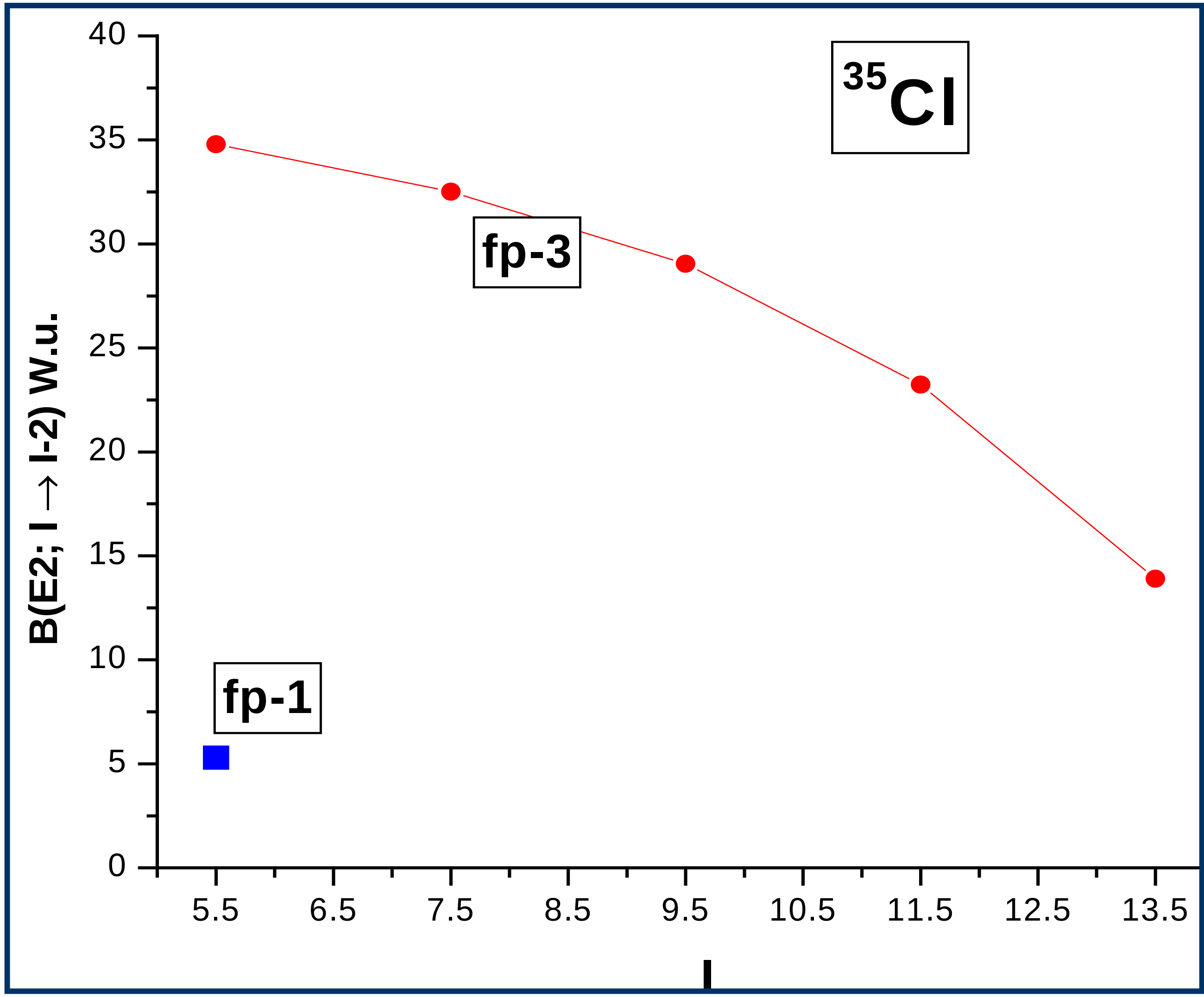

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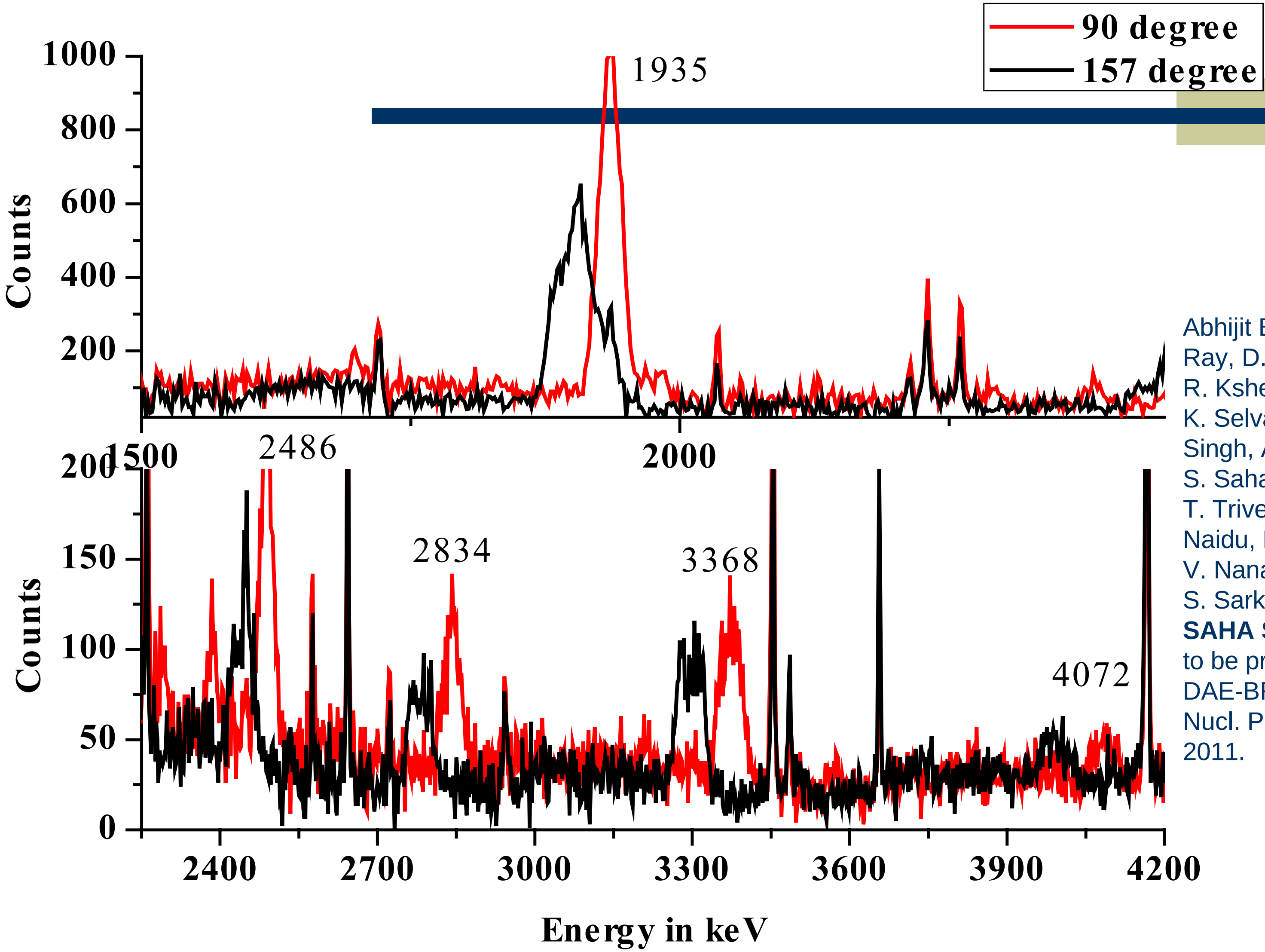
^{34}Cl



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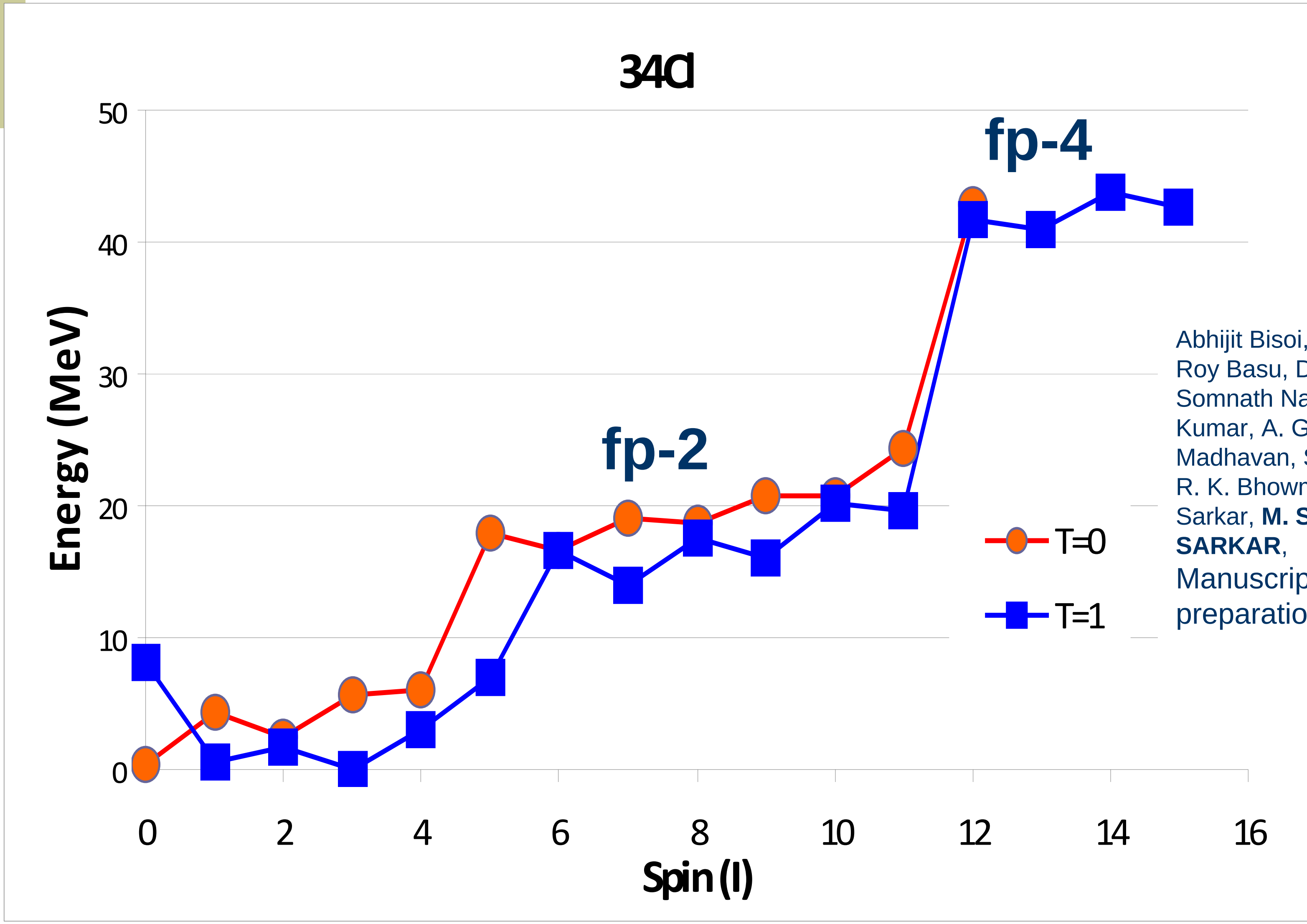

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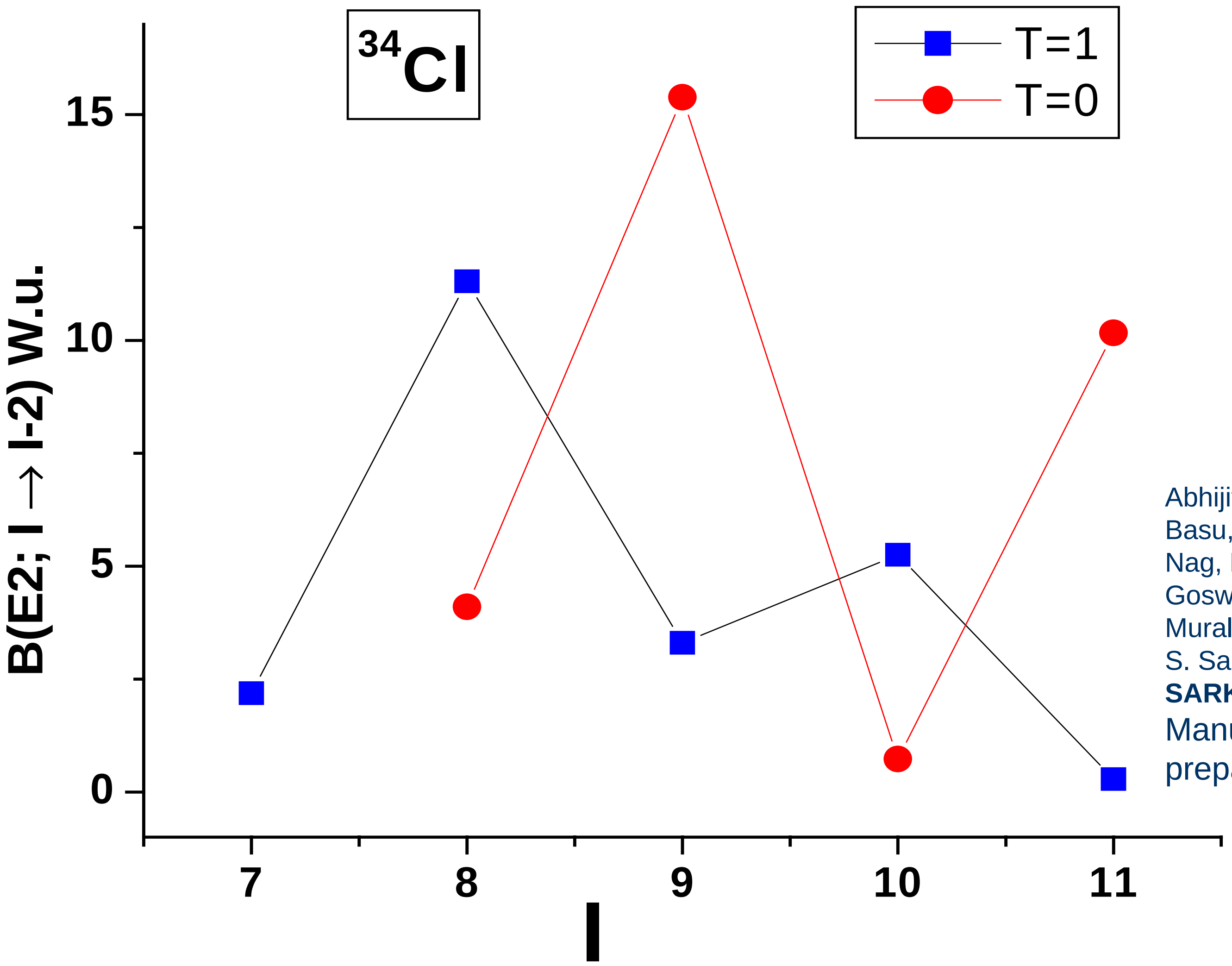

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THANK YOU