Level Structure of ^{32,34}P : What do we learn about the $f_{7/2}$ –$p_{3/2}$ energy gap ?

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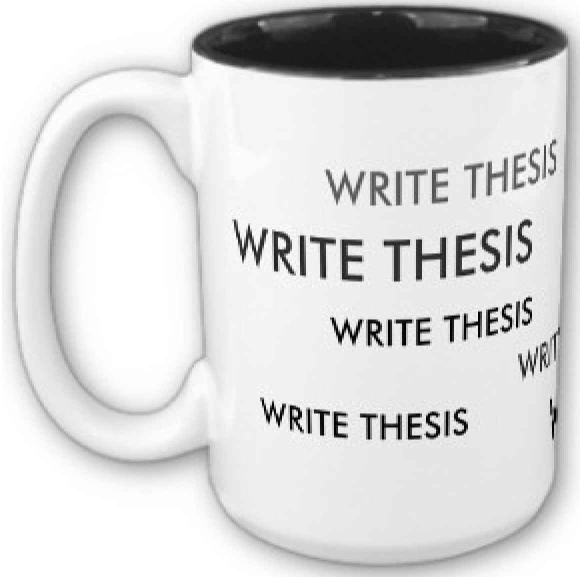

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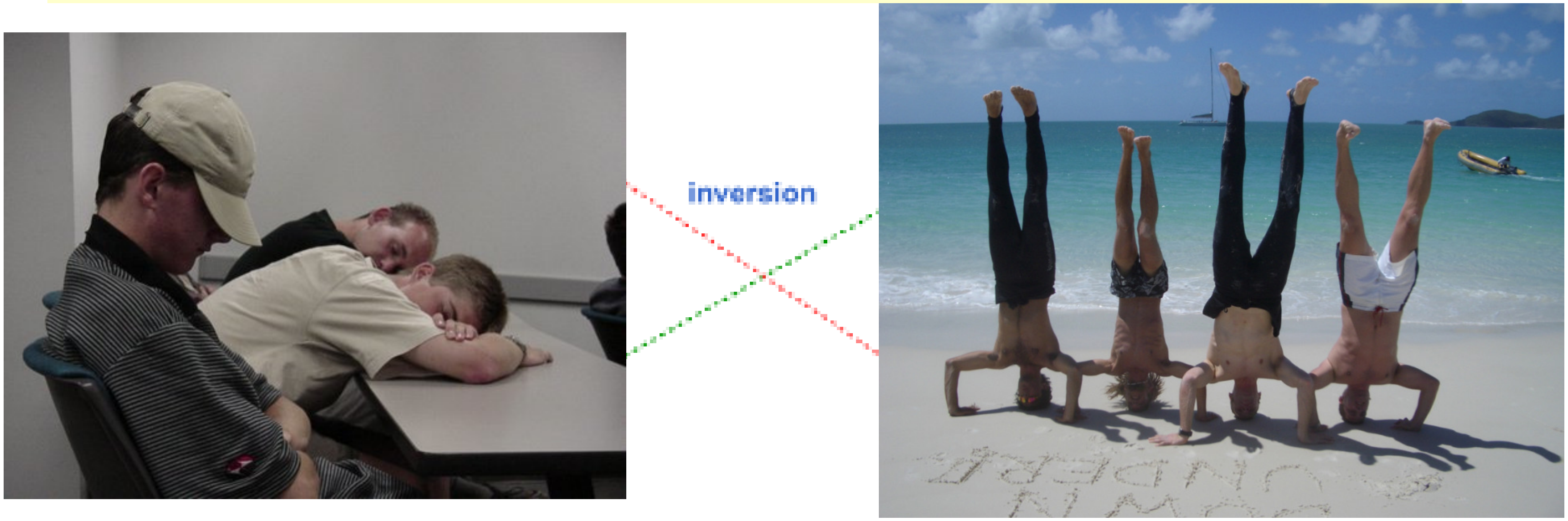
Introduction & Motivation



Shell structure:
Nucleon motion in mean field

→

Inversion:
Domination of residual nucleon-nucleon interaction

What happens to the nuclear structure in between the valley of stability
And the island of inversion?

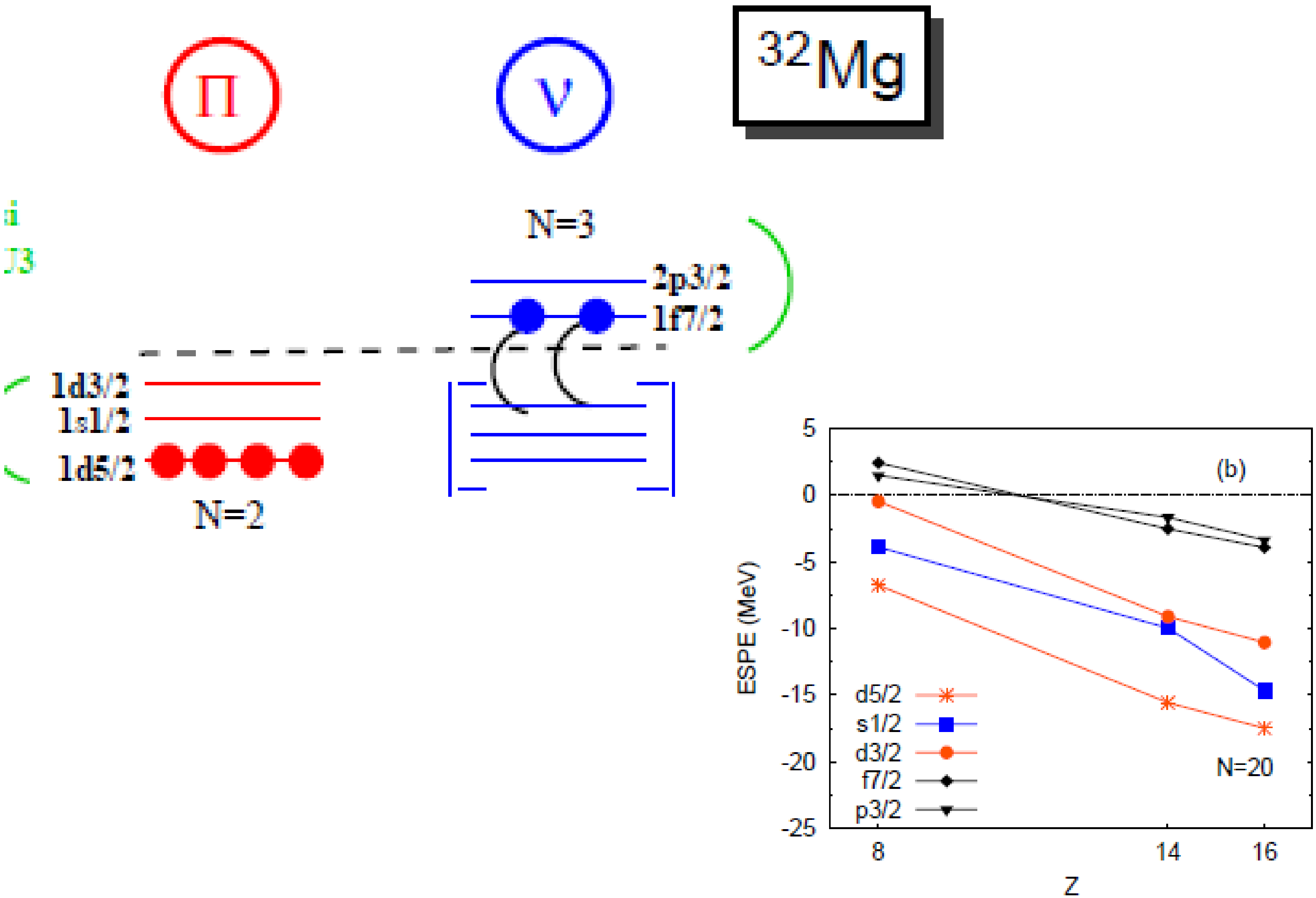
The region between: The valley of stability & Island of Inversion

is a highly transitional region

Investigations into the extent of the island of inversion and the transition from stable nuclei to neutron-rich nuclei will lead to a greater understanding of the evolution of shell structure.

Z \ N	14	15	16	17	18	19	20	21	22	23
16			^{32}S	^{33}S	^{34}S	^{35}S	^{36}S	^{37}S	^{38}S	^{39}S
15			^{31}P	^{32}P	^{33}P	^{34}P	^{35}P	^{36}P	^{37}P	^{38}P
14	^{28}Si	^{29}Si	^{30}Si	^{31}Si	^{32}Si	^{33}Si	^{34}Si	^{35}Si	^{36}Si	^{37}Si
13	^{27}Al	^{28}Al	^{29}Al	^{30}Al	^{31}Al	^{32}Al	^{33}Al	^{34}Al	^{35}Al	^{36}Al
12	^{26}Mg	^{27}Mg	^{28}Mg	^{29}Mg	^{30}Mg	^{31}Mg	^{32}Mg	^{33}Mg	^{34}Mg	^{35}Mg
11	^{25}Na	^{26}Na	^{27}Na	^{28}Na	^{29}Na	^{30}Na	^{31}Na	^{32}Na	^{33}Na	^{34}Na
10	^{24}Ne	^{25}Ne	^{26}Ne	^{27}Ne	^{28}Ne	^{29}Ne	^{30}Ne	^{31}Ne	^{32}Ne	
9	^{23}F	^{24}F	^{25}F	^{26}F	^{27}F		^{29}F			
8	^{22}O	^{23}O	^{24}O							

Z ↑ N →



π
ν
^{32}Mg
N=3
2p3/2
1f7/2
1d3/2
1s1/2
1d5/2
N=2
(b)
ESPE (MeV)
Z
N=20
d5/2
s1/2
d3/2
f7/2
p3/2

In fact, the shell does evolve, ... due to the tensor force.

[Otsuka et al., *PRL* 95 (05) 232502]

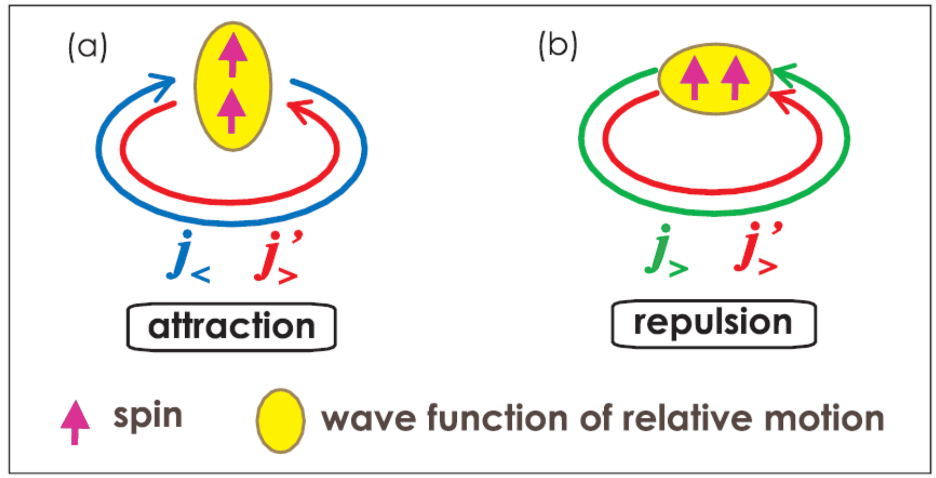
[Otsuka et al., *PRL* 97 (06) 162501]

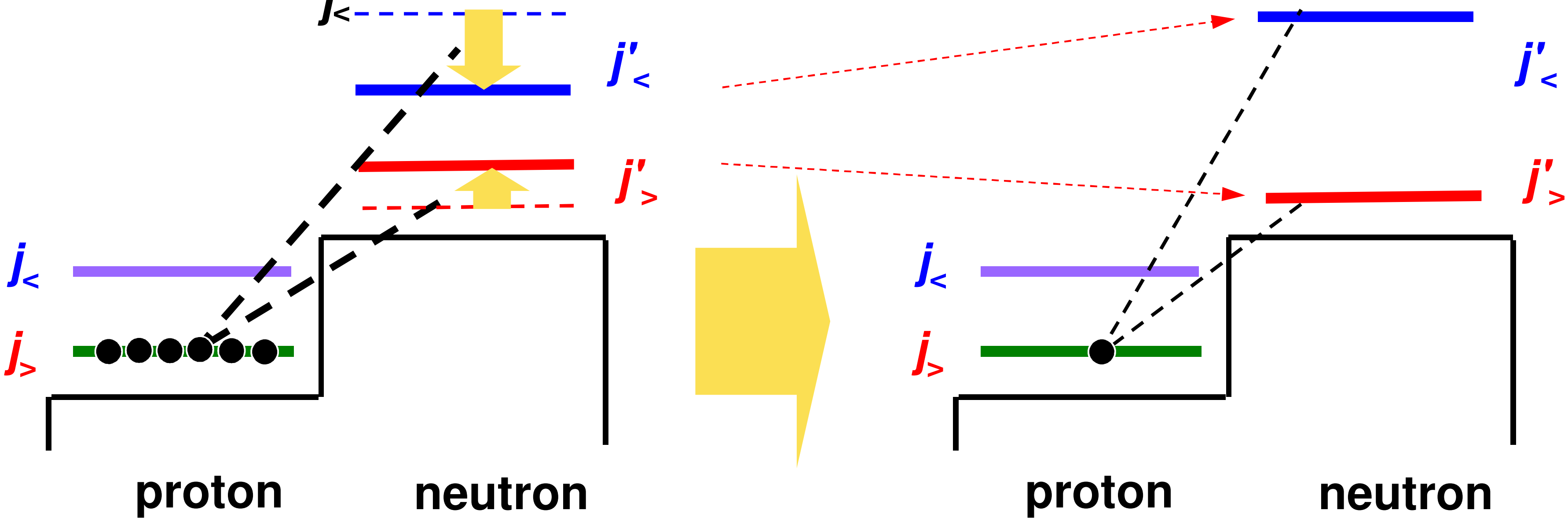
- **Monopole energy of the tensor interaction**

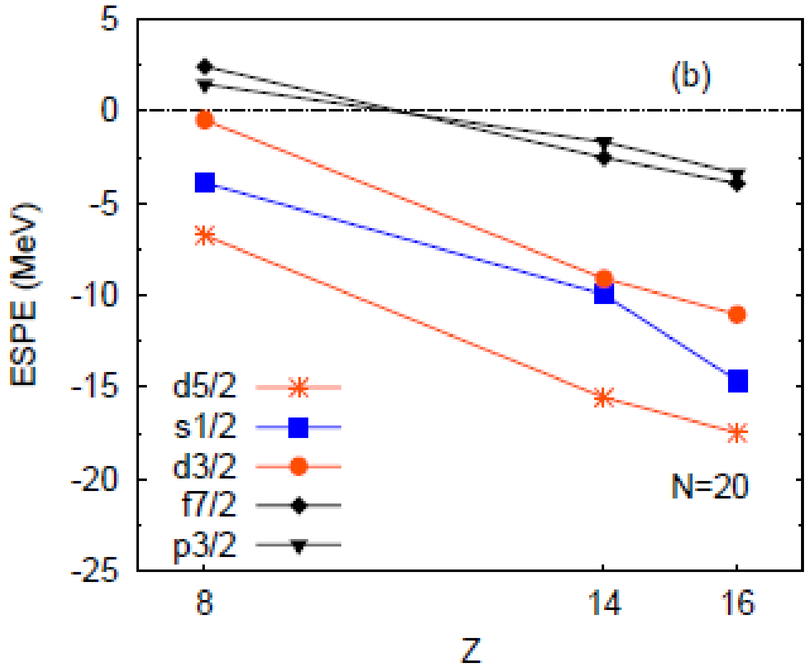
$$V^{\mathrm{T}}_{j,j'} = \frac{\sum_J (2J+1)\langle jj'|V|jj'\rangle_{JT}}{\sum_J (2J+1)}$$

is

- attractive for $j_> - j_<'$, $j_< - j_>'$
- repulsive for $j_> - j_>'$, $j_< - j_<'$







Thus, the single-particle orbits <u>may migrate</u> leading to a possible change in shell structure.

Important to have experimental spectroscopic study in this transitional region of the nuclear landscape

Level Energy → γ^n matrices

Spin → Angular Correlation

Parity → Polarization

Lifetimes → Lineshape

Test of shell models

Whether the N=20 shell gap decreases here?

Is there a need to decrease SPE'S for these nuclei?

How to populate neutron-rich nuclei?

Reactions employed in earlier investigations of nuclei in the vicinity of the island of inversion

β-decay

Nathan et al,PRC 15,1448(1977)

Deuteron inelastic scattering

I.Iwasa et al., PRC67 (2003)064315

Heavy ion collision

Fornal et al PRC49 ,2413(1994)

Deep inelastic

R.Broda,J.Phys.G32,R151(2006)

Intermediate energy coulomb excitation

Pritychenko et al, PRC62,051601®(2000)

Transfer/deep inelastic

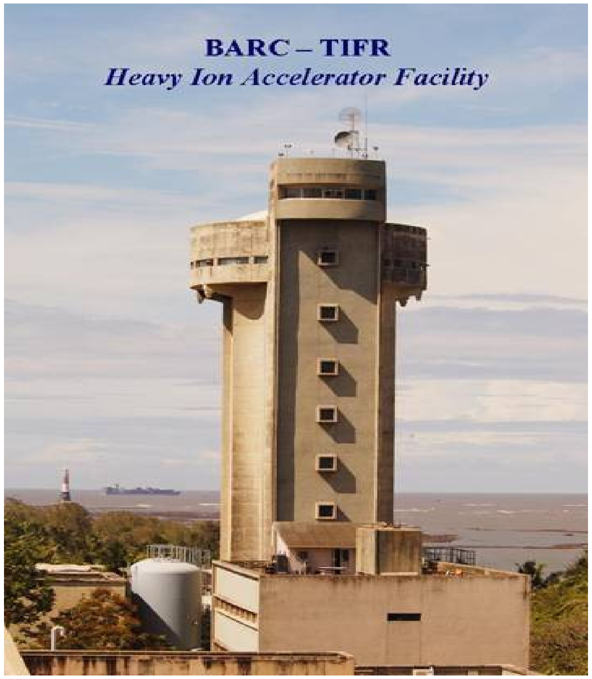
Krishichayan et al, Eur.Phys.J.A29,151(2006)

Limited in terms of population of higher angular momentum states.
Coincident binary emission has to be taken care of for transfer/deep inelastic reaction.
Complicated setup and more presorting required

Solution:

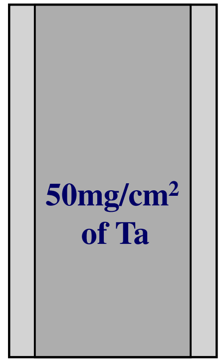
Use Fusion-evaporation reaction using a neutron-rich target and/or a neutron-rich projectile

Experimental Details



$^{18}O+^{18}O$@34MeV

TARGET



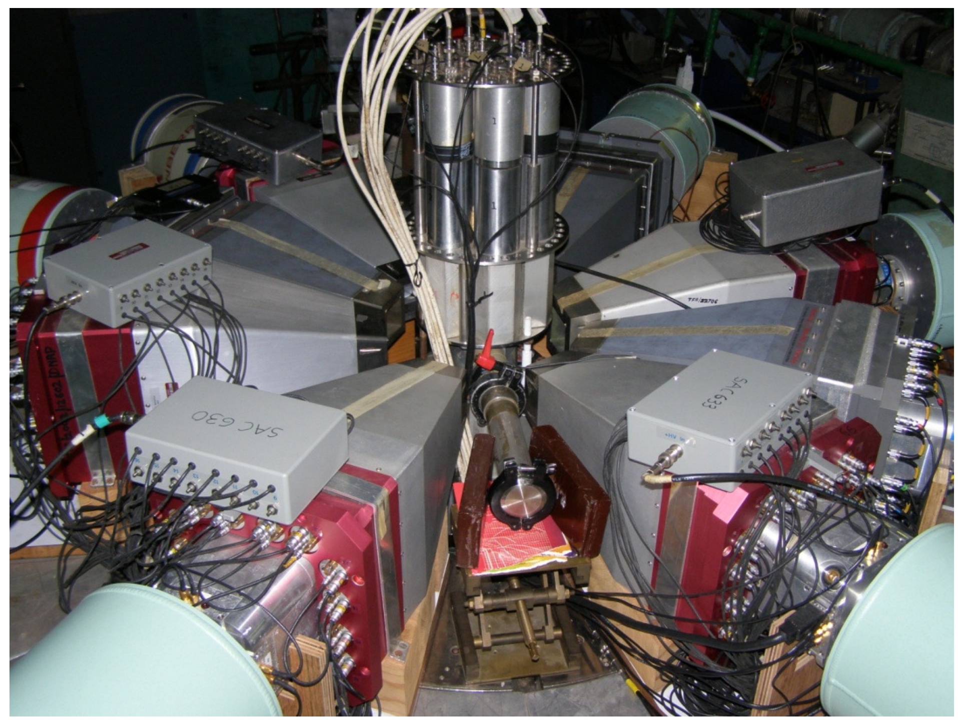
^{18}O (thickness ~1.6mg/cm^2)

An event was recorded when : **Two clovers fire in coincidence**

Beam	**^{18}O**
Beam current	**~ 20 nA**
Beam energy	**34 MeV**
Target	**^{18}O (Tantalum Oxide)**
Detector configuration	**7CLOVER detectors**
Event rate	**~ 1.3k/s**
Events recorded	**~1 Billion γ-γ coincidences**

DATA Acquisition System:
CAMAC Based multi-parameter system "LAMPS"

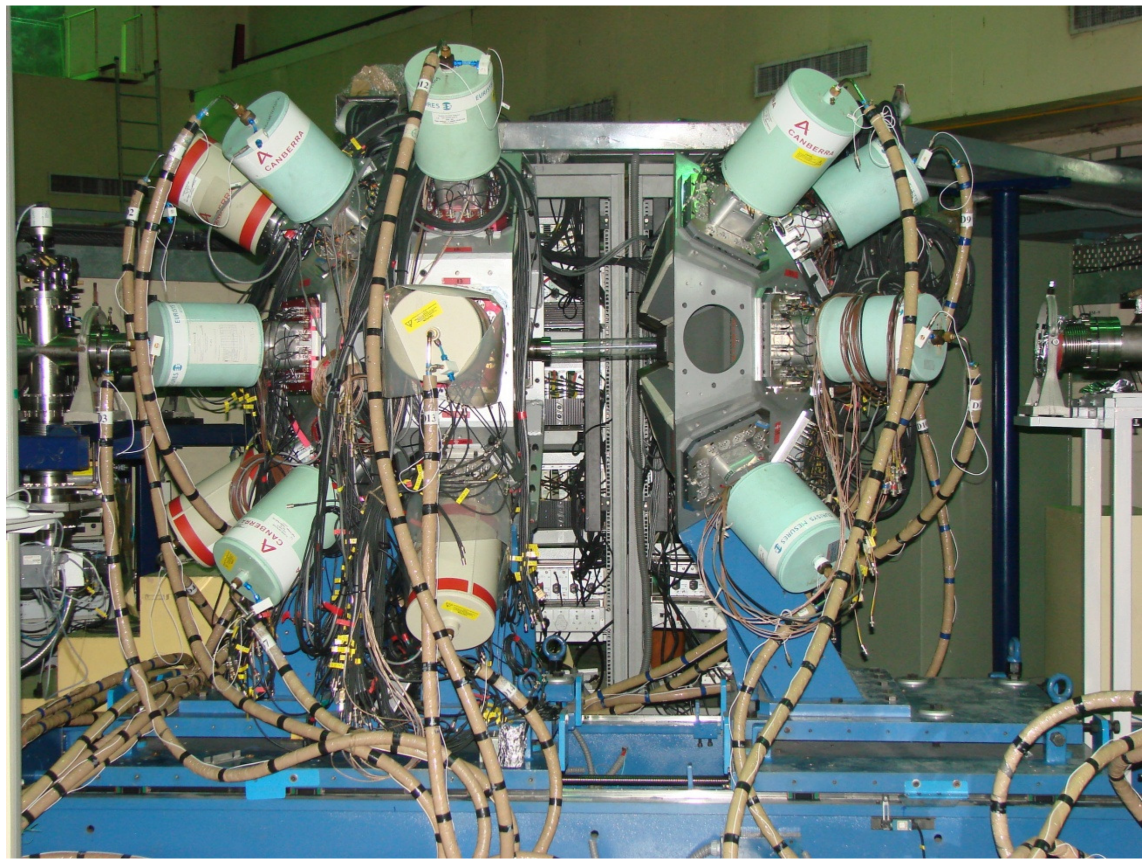
Detector Array



15UD Pelleton facility

$^{16}O+^{18}O$@34MeV

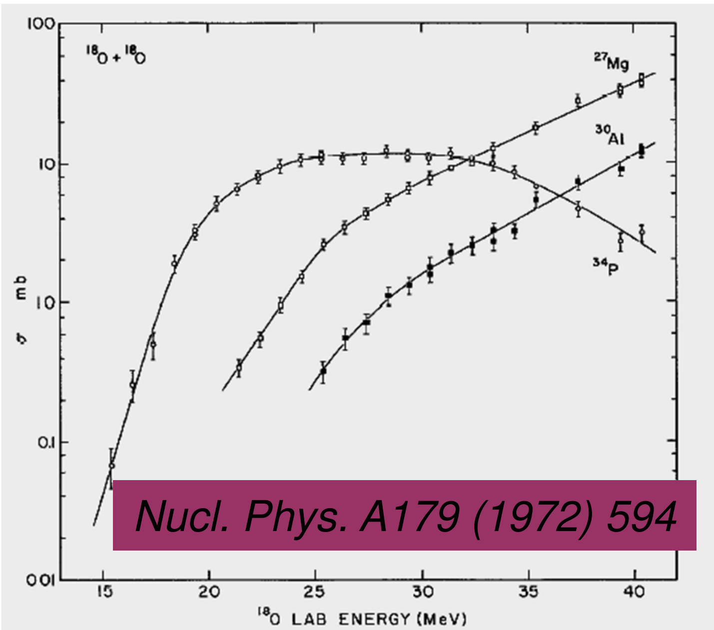
INDIAN NATIONAL GAMMA ARRAY



Inter University Accelerator Centre, New Delhi

18 Clover detectors:
3 at ~32^0, 4 at ~57^0,
5 at ~90^0, 3 at ~123^0,
3 at ~148^0.

Fusion-evaporation has resulted in considerable enhancement of production of ^{34}P



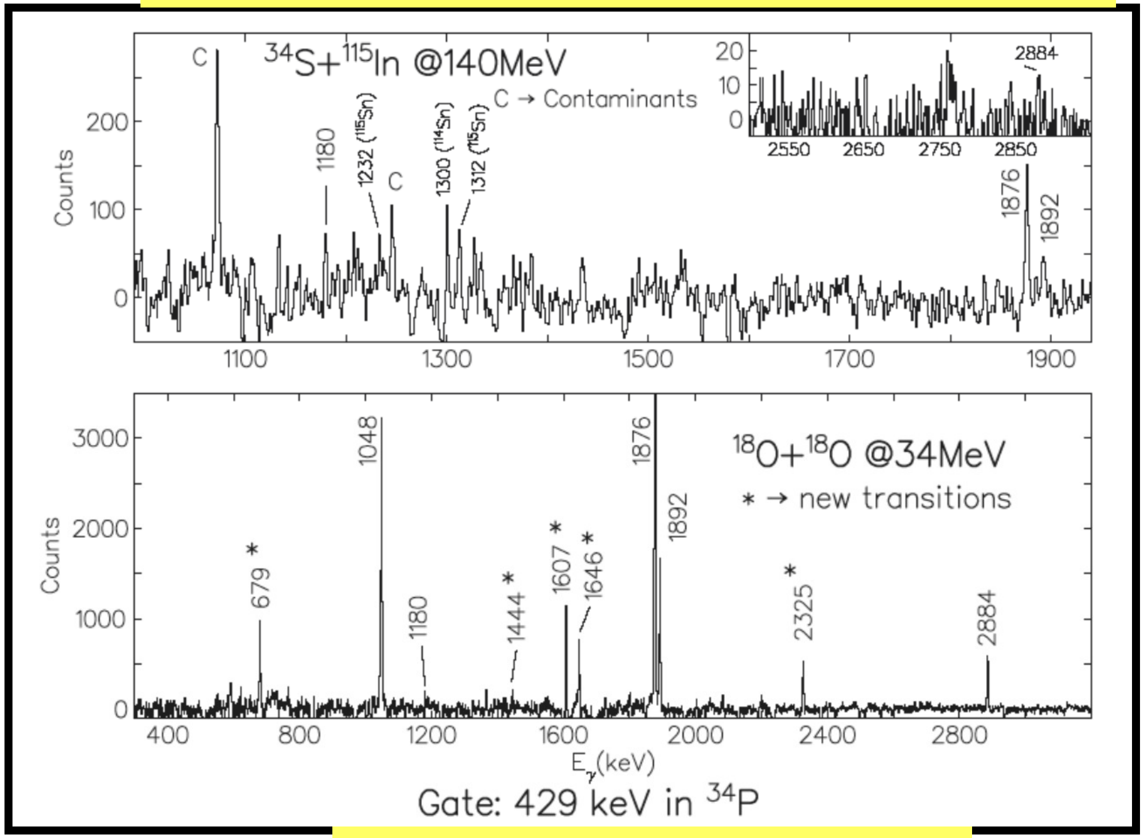
Nucl. Phys. A179 (1972) 594

Fig. 3. Excitation function of the residual nuclei ^{27}Mg, ^{30}Al and ^{34}P produced in the compound-nucleus reaction $^{18}O + ^{18}O$.

Excitation function of residual nuclei produced in the compound nuclear Reaction $^{18}O + ^{18}O$.

Krishichayan *et al* EPJA 29,151 (2006)

Transfer Reactions/Deep-inelastic Reactions

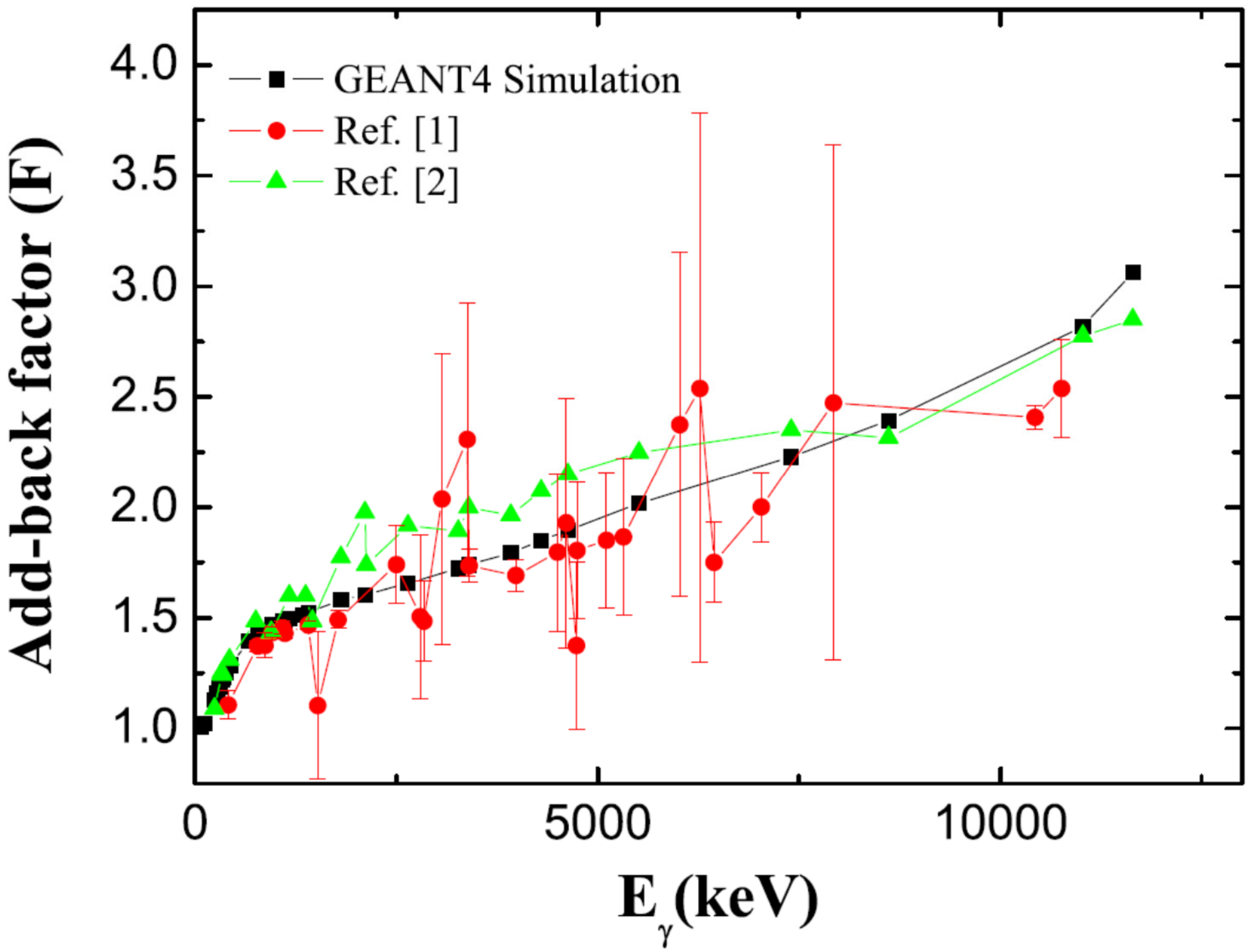


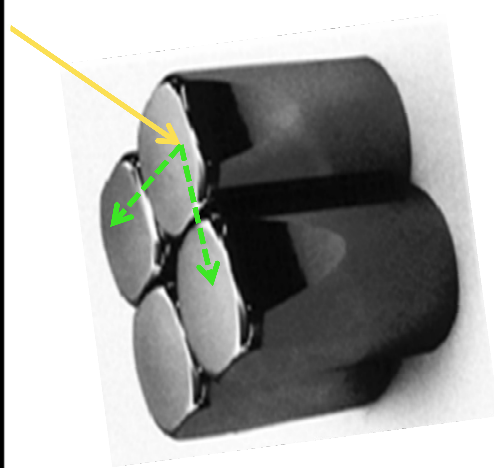
Fusion-evaporation channel

R. Chakrabarti *et al* PRC 80, 034326 (2009)

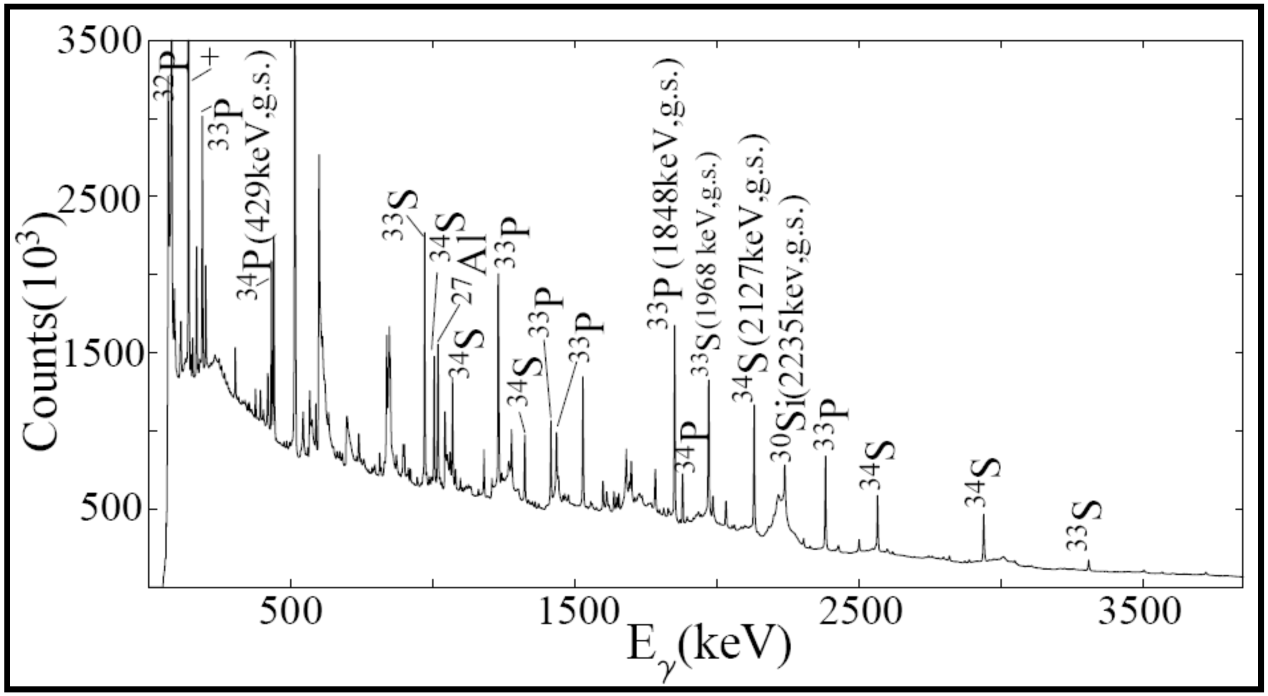
How to investigate the structure of the Nucleus?

In-beam Gamma ray spectroscopy





Results

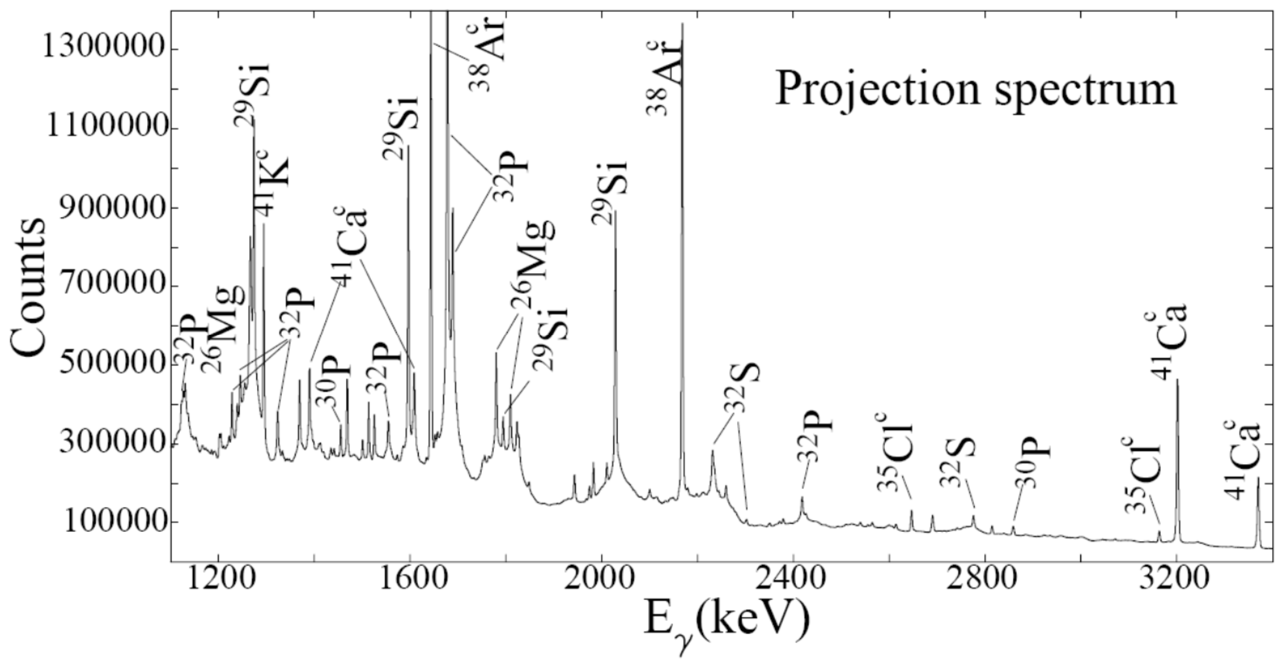


Projection spectrum:
$^{18}O + ^{18}O$ @ 34 MeV

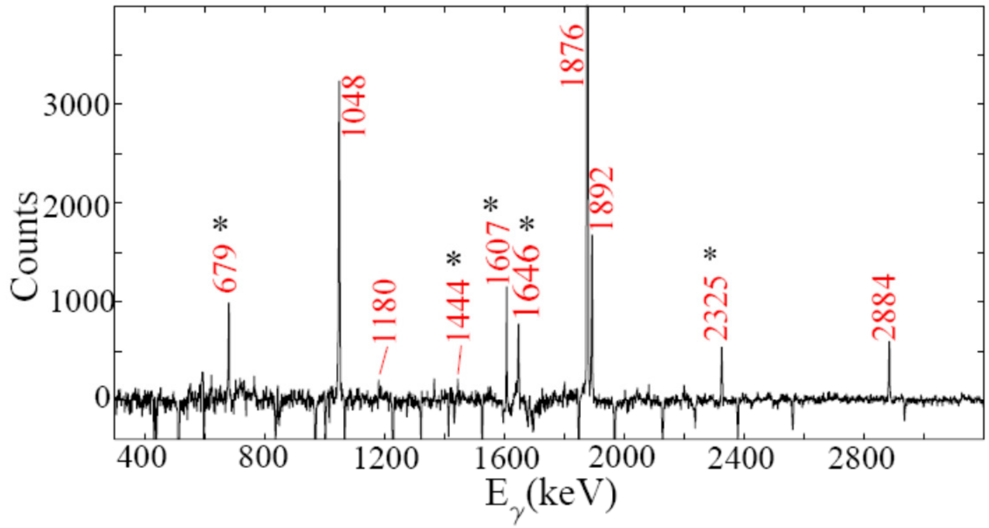
Populated nuclei:
$^{33,34}S$, $^{33,34}P$, $^{30,31,32}Si$

Projection spectrum:
$^{16}O + ^{18}O$ @ 34 MeV

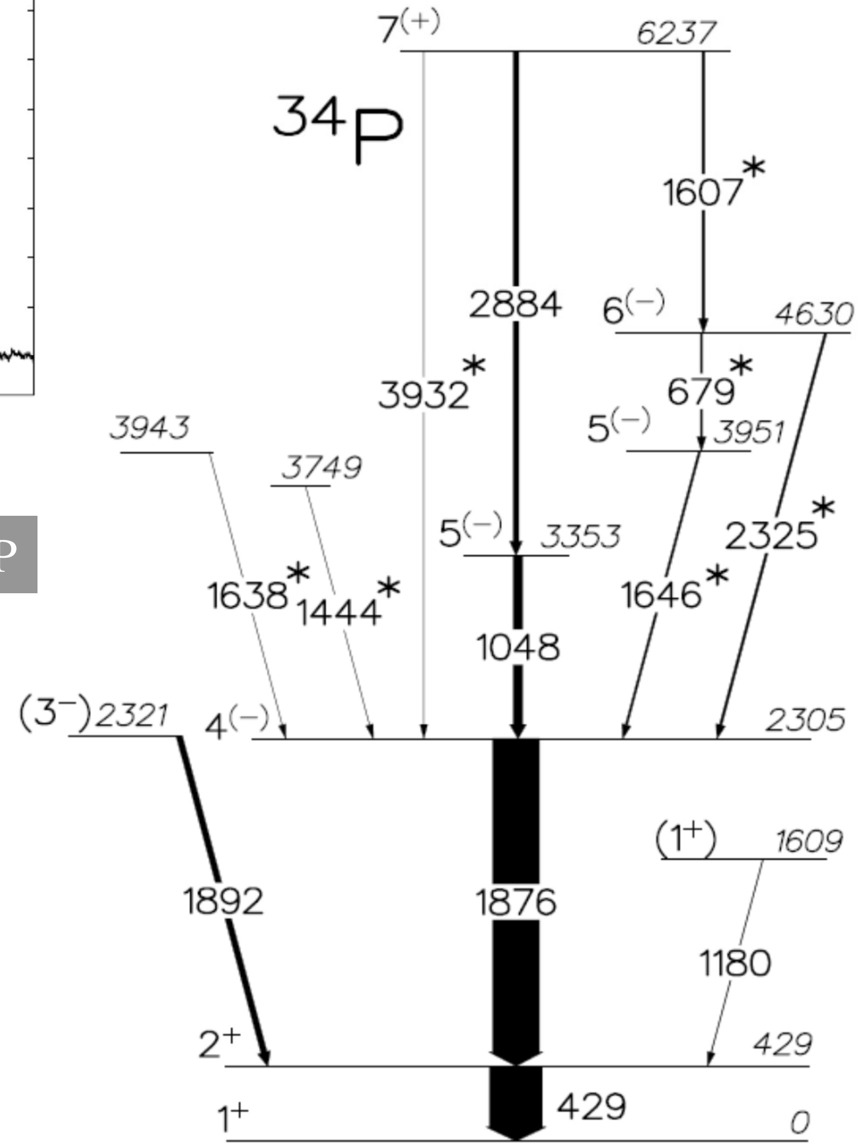
Populated nuclei:
^{32}S, $^{30,31,32}P$, $^{29,30}Si$



From $^{18}O + ^{18}O$ @ 34 MeV

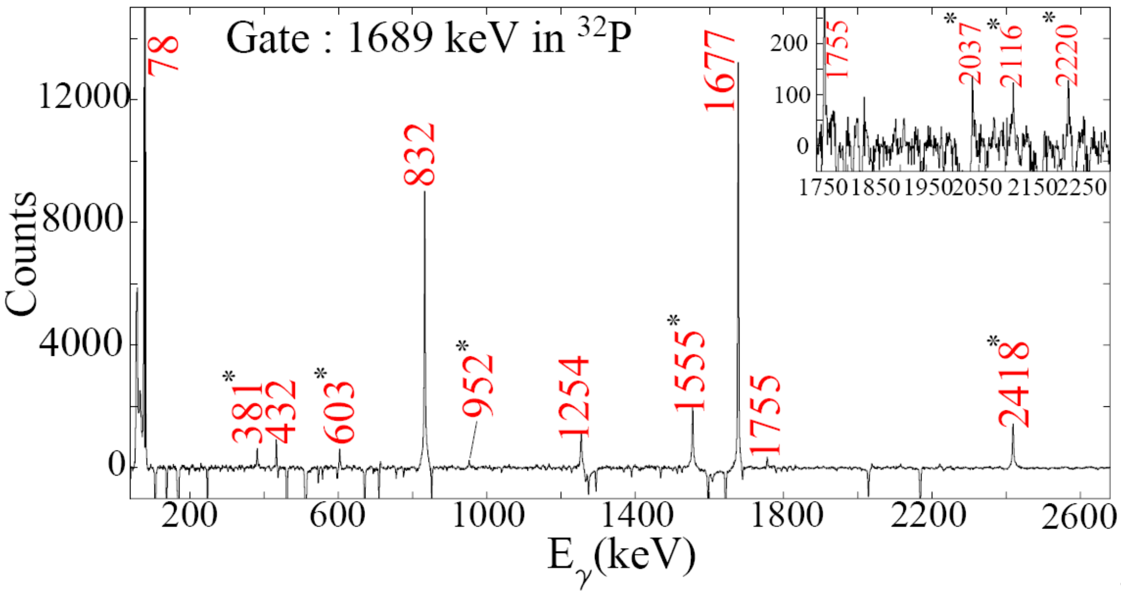


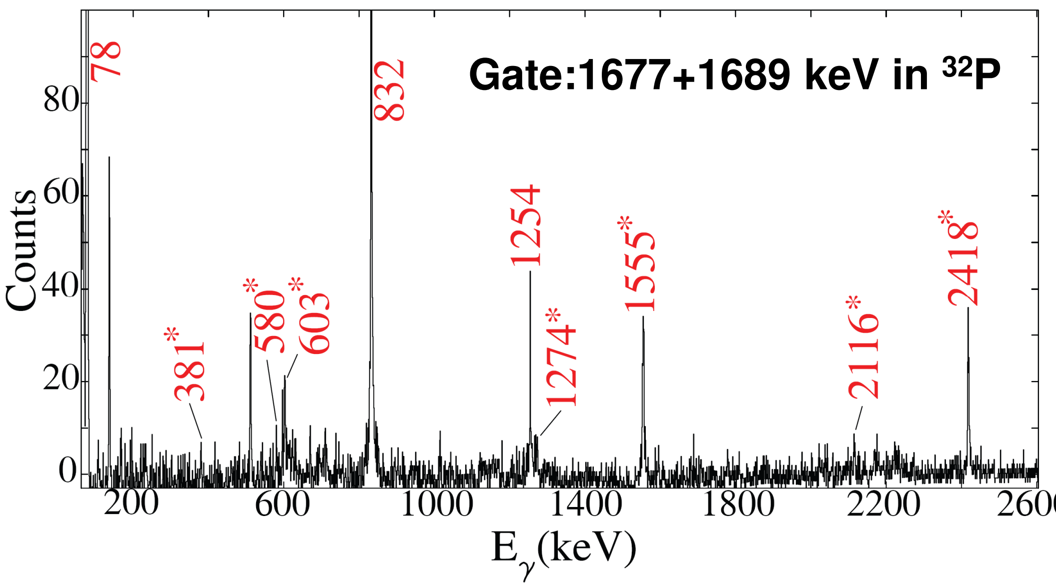
Coincidence spectrum with gate on 429 keV in ^{34}P

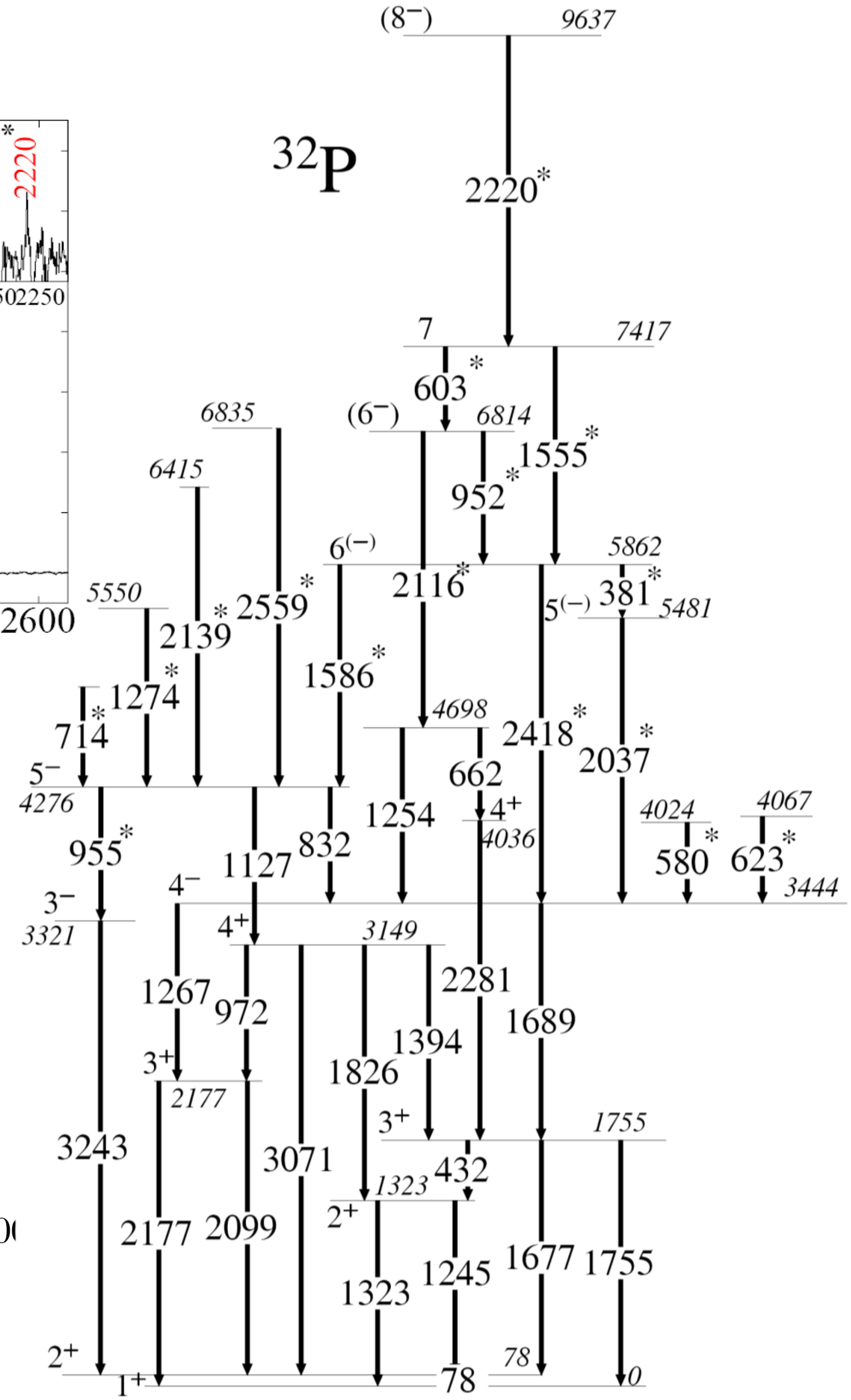


***Phys. Rev. C* 80, 034326 (2009)**

From ^{16}O + ^{18}O @ 34 MeV







In Press Phys. Rev. C

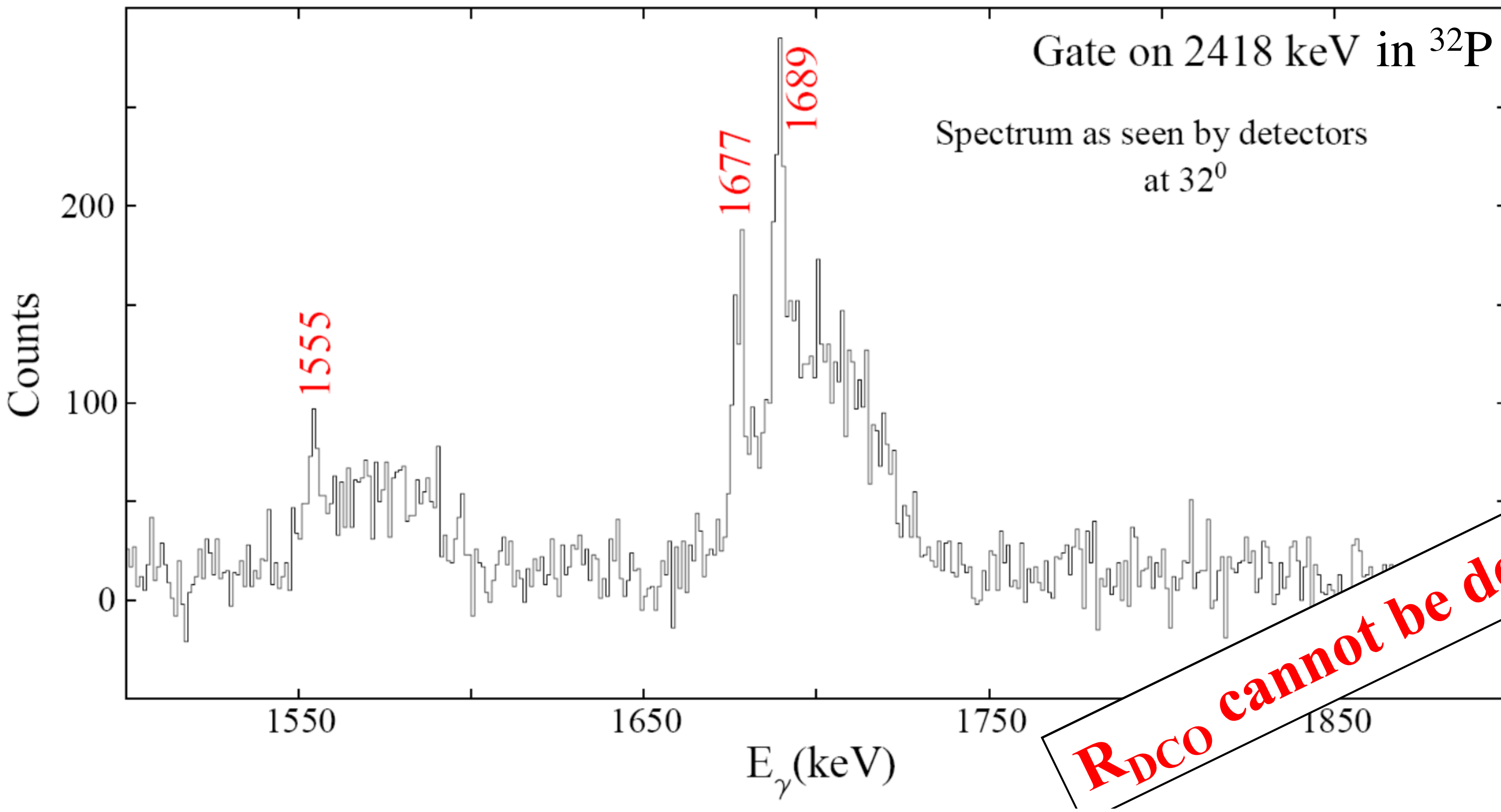
Determination of Mulipolarity

$^{16}O + {}^{18}O$ @ 34MeV

Standard Method:

$$R_{DCO} = \frac{I_{\gamma 1} \text{ at } 32^0 \text{ or } 148^0 \text{, gated with } \gamma_2 \text{ at } 90^0}{I_{\gamma 1} \text{ at } 90^0 \text{, gated with } \gamma_2 \text{ at } 32^0 \text{ or } 148^0}$$

Gate on 1677 kev or 1689 keV at detectors at 32^0 or 148^0 not possible due to Doppler effects !!



R_{DCO} cannot be determined!

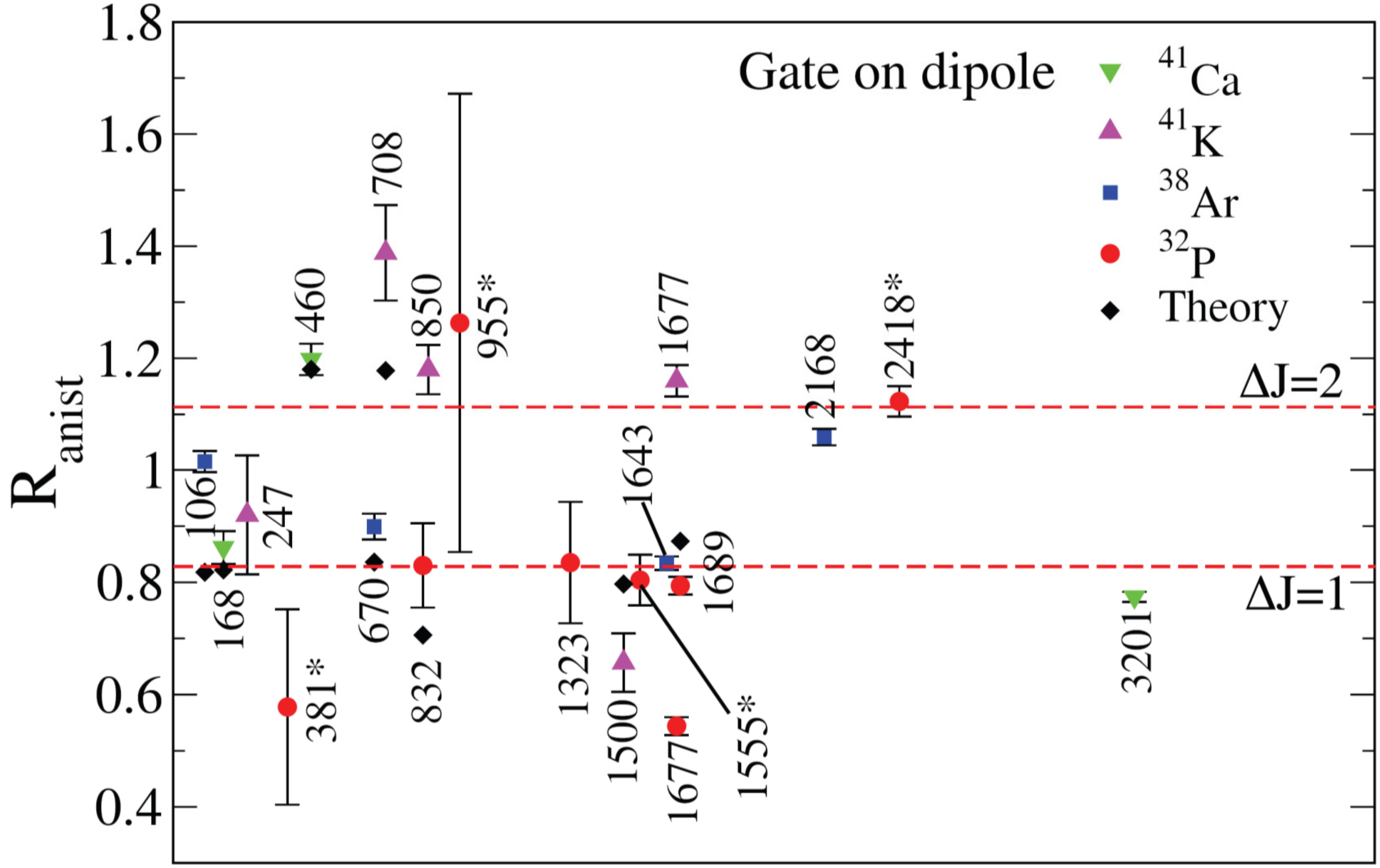
Alternative Method

Determination of Mulipolarity

$^{16}O + ^{18}O$ @ 34MeV

Asymmetric γ-γ matrices:
57^0 Vs 90^0
32^0 Vs 90^0

$$R_{anist} = \frac{I_{\gamma 1} \text{ at } 32^0 \text{ , gated with } \gamma_2 \text{ at } 90^0}{I_{\gamma 1} \text{ at } 57^0 \text{ , gated with } \gamma_2 \text{ at } 90^0}$$



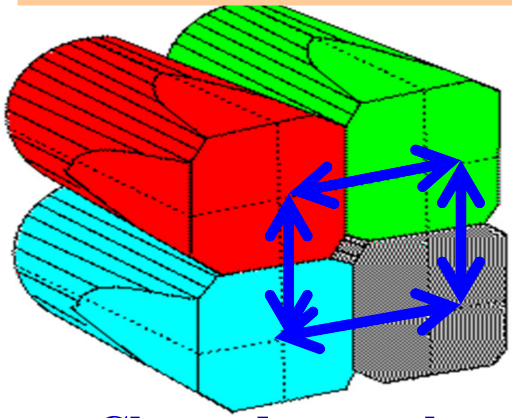
Calibration points: Transitions with known multipolarities in other strongly populated nuclei exhibiting no lineshape

Theoretical calculations done using code: ANGCOR

Magnetic or Electric??

✓ Electric transition results in a preferential scattering in perpendicular direction (with respect to the reaction plane).

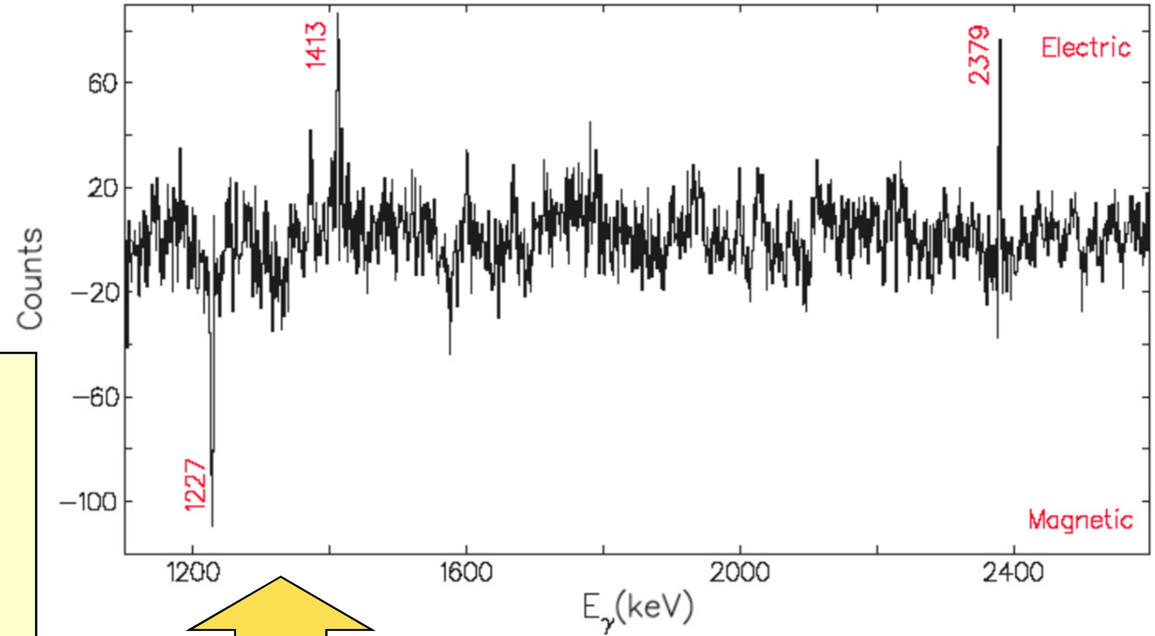
✓ While a magnetic transition indicates a preferential scattering in parallel direction.



Clover detector has *uniquely* facilitated polarization measurements. Each crystal acts as a scatterer while the adjacent crystals act as absorbers.

Asymmetric matrices generated:

- **One axis corresponds to perpendicular or parallel scattered events in clovers at 90^0**
- **Other axis corresponds to total energy deposited in any of the other detectors.**



Background subtracted difference spectrum for perpendicular and parallel coincidences in ^{33}P (gate on 1848 keV). The electric γ–ray transition shows positive peak, whereas the magnetic γ–ray transition shows negative peak.

Experimental Linear Polarization measurement

$$\Delta_{IPDCO} = \frac{aN_{\perp} - N_{\parallel}}{aN_{\perp} + N_{\parallel}}$$

$N_{\perp}$ = Number of photons with a given energy scattered along the direction ⊥ to the reaction plane

$N_{\parallel}$ = Number of photons with a given energy scattered along the direction ∥ to the reaction plane

$$a = \frac{N_{\parallel}(unpolarized)}{N_{\perp}(unpolarized)}$$

$$P_{exp}(\theta) = \Delta / Q,$$

Theoretical Polarization measurement

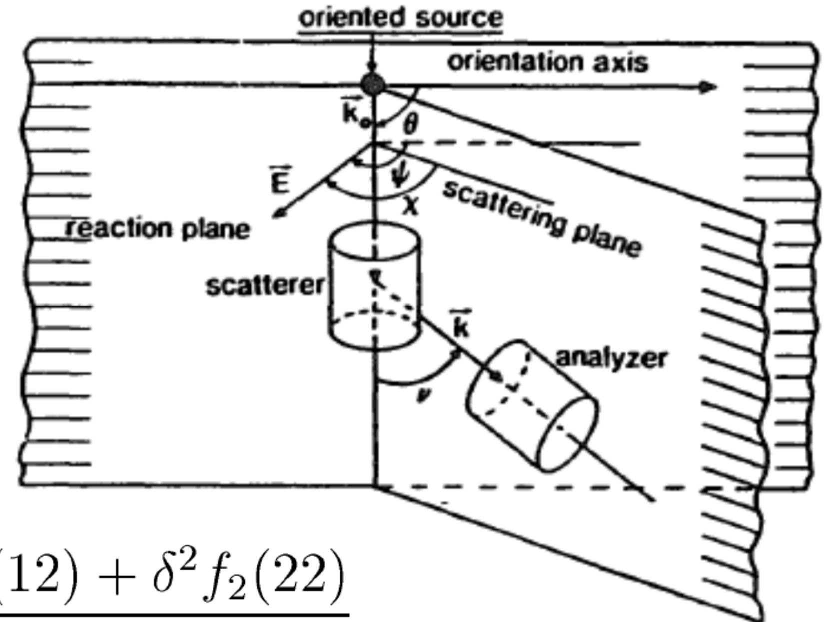
$$P_{cal}(90^0) = \pm \frac{3a_2H_2 - 7.5a_4H_4}{2 - a_2 + 0.75a_4}$$

H_2 and H_4 are linear polarization mixing coefficients

(Derived for L = 2, L' =3 transitions)

a_2 and a_4 are angular distribution coefficients

$$P(\theta) = \frac{W(\theta, \psi = 0) - W(\theta, \psi = \pi/2)}{W(\theta, \psi = 0) + W(\theta, \psi = \pi/2)}$$



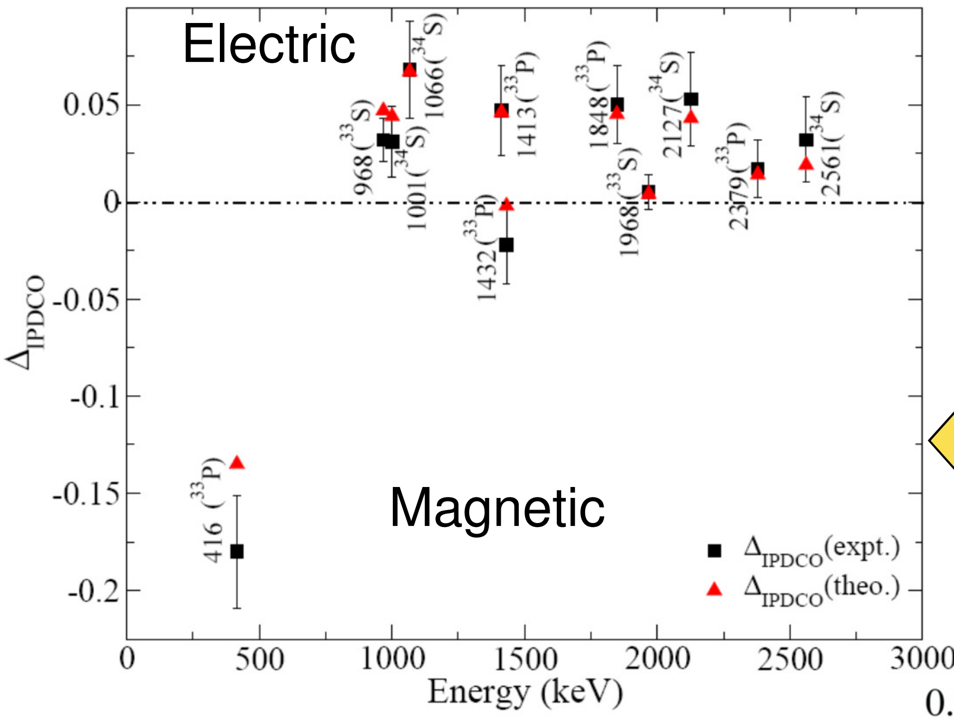
$$P_{cal}(90^0) = \pm \frac{3a_2H_2 - 7.5a_4H_4}{2 - a_2 + 0.75a_4}$$

$$H_2(L = 1, L^{'} = 2) = \frac{f_2(11) - (2/3)\delta f_2(12) + \delta^2 f_2(22)}{f_2(11) + 2\delta f_2(12) + \delta^2 F_2(22)}$$

$$H_4(L = 1, L^{'} = 2) = -1/6$$

$$H_2(L = 2, L^{'} = 3) = \frac{-f_2(22) - \delta f_2(23) + (2/3)\delta^2 f_2(33)}{f_2(22) + 2\delta f_2(23) + \delta^2 f_2(33)}$$

$$H_4(L = 2, L^{'} = 3) = \frac{5 f_4(22) - 2\delta f_4(23) + 20\delta f_4(33)}{30(f_4(22) + 2\delta f_4(23) + \delta^2 f_4(33))}$$



Δ_{IPDCO} = +ve → Electric

= -ve → Magnetic

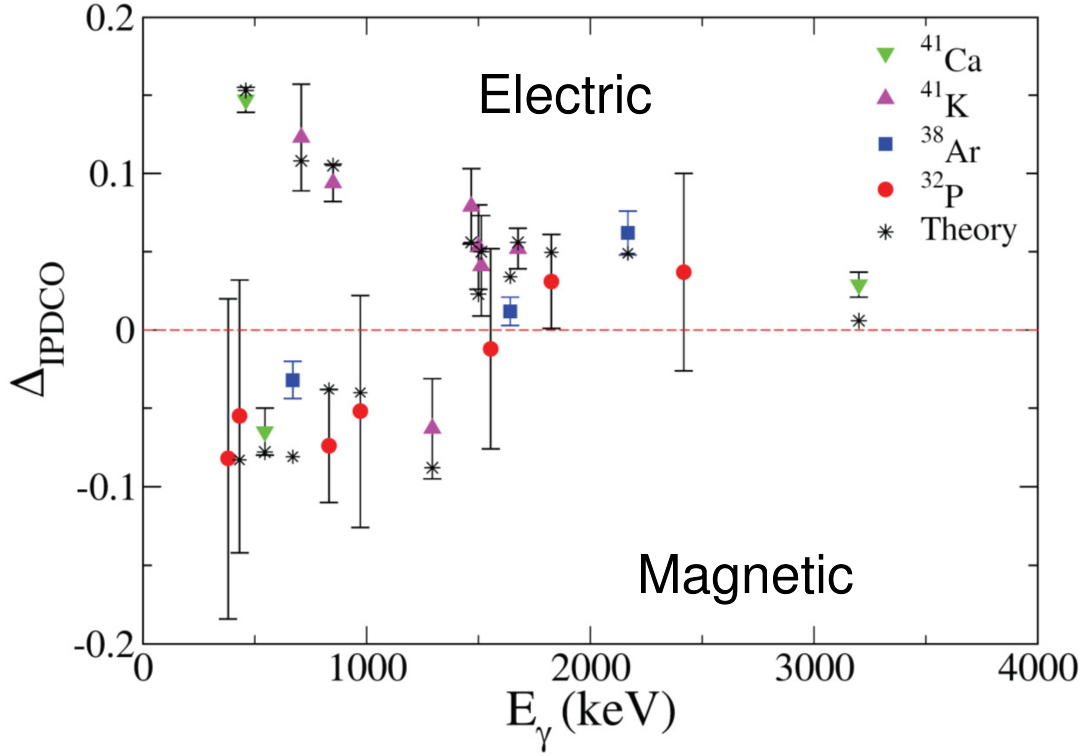
~ 0 → Mixed

^{18}O + ^{18}O @ 34MeV

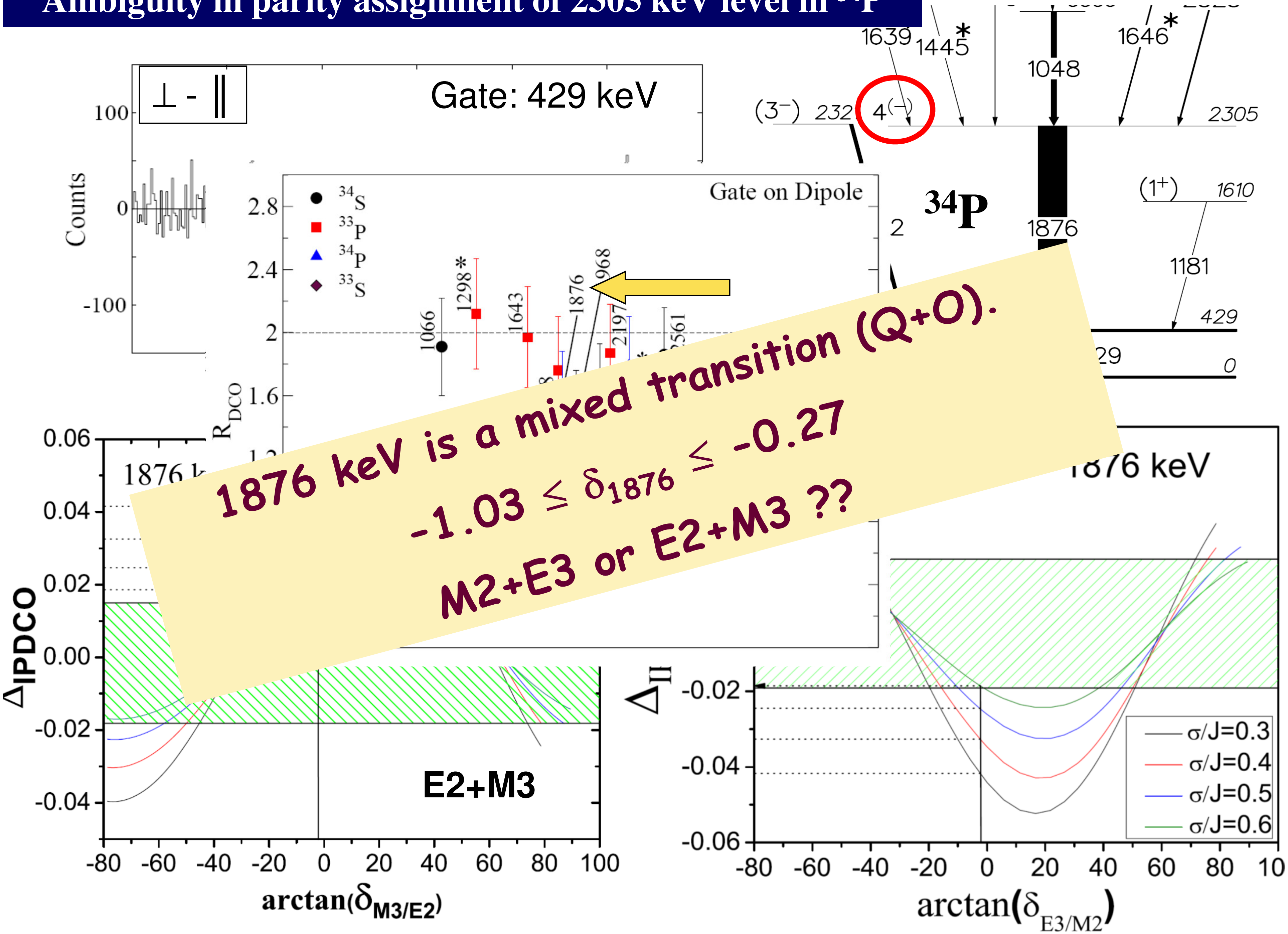
$$\pi(ML) = (-1)^{L+1}$$

$$\pi(EL) = (-1)^{L}$$

^{16}O + ^{18}O @ 34MeV



Ambiguity in parity assignment of 2305 keV level in ^{34}P



Lifetime of 2305 keV level : 0.3ns ≤ $t_{1/2}$ ≤ 2.5ns [1]

Half-life (ns)	Mixing ratio (δ)	Reduced transition probabilities			
		$M2/E3$		$E2/M3$	
		$B(M2)$ (W.u.)	$B(E3)$ (W.u.)	$B(E2)$ (W.u.)	$B(M3)$ (W.u.)
0.3	−1.03	0.207	372.681	0.006	12520.654
	−0.27	0.397	49.191	0.012	1652.638
2.5	−1.03	0.025	44.722	0.001	1502.478
	−0.27	0.048	5.903	0.001	198.317

Conclusion:
1876 keV is plausibly a M2+E3 transition
2305 keV level : $J^{\pi} = 4^{-}$

[1] M. Asai, T. Ishii, A. Makishima, M. Ogawa, and M. Matsuda, in *Proceedings of the Third International Conference on Fission and Properties of Neutron-Rich Nuclei*, edited by J. H. Hamilton, A. V. Ramayya, and H. K. Carter (World Scientific, Singapore, 2002), pp. 295–297.

Half-life of the $I^{\pi} = 4^{-}$ Intruder State in ^{34}P: $M2$ Transition Strengths Approaching the Island of Inversion.

P.J.R Mason[a,*], T. Alharbi[a,b], P.H. Regan[a], N. Mărginean[c], Zs. Podolyàk[a], N. Alkhomashi[d], P.C. Bender[e], M. Bowry[a], M. Bostan[f], D. Bucurescu[c], A.M. Bruce[g], G. Căta-Danil[c], I. Căta-Danil[c], R. Chakrabarti[h], D. Deleanu[c], P. Detistov[i], M.N. Erduran[j], D. Filipescu[c], U. Garg[k], T. Glodariu[c], D. Ghiţă[c], S.S. Ghugre[h], A. Kusoglu[f], R. Mărginean[c], C. Mihai[c], M. Nakhostin[a], A. Negret[c], S. Pascu[c], C. Rodríguez Triguero[g], T. Sava[c], E.C. Simpson[a], A.K. Sinha[h], L. Stroe[c], G. Suliman[c], N.V. Zamfir[c]

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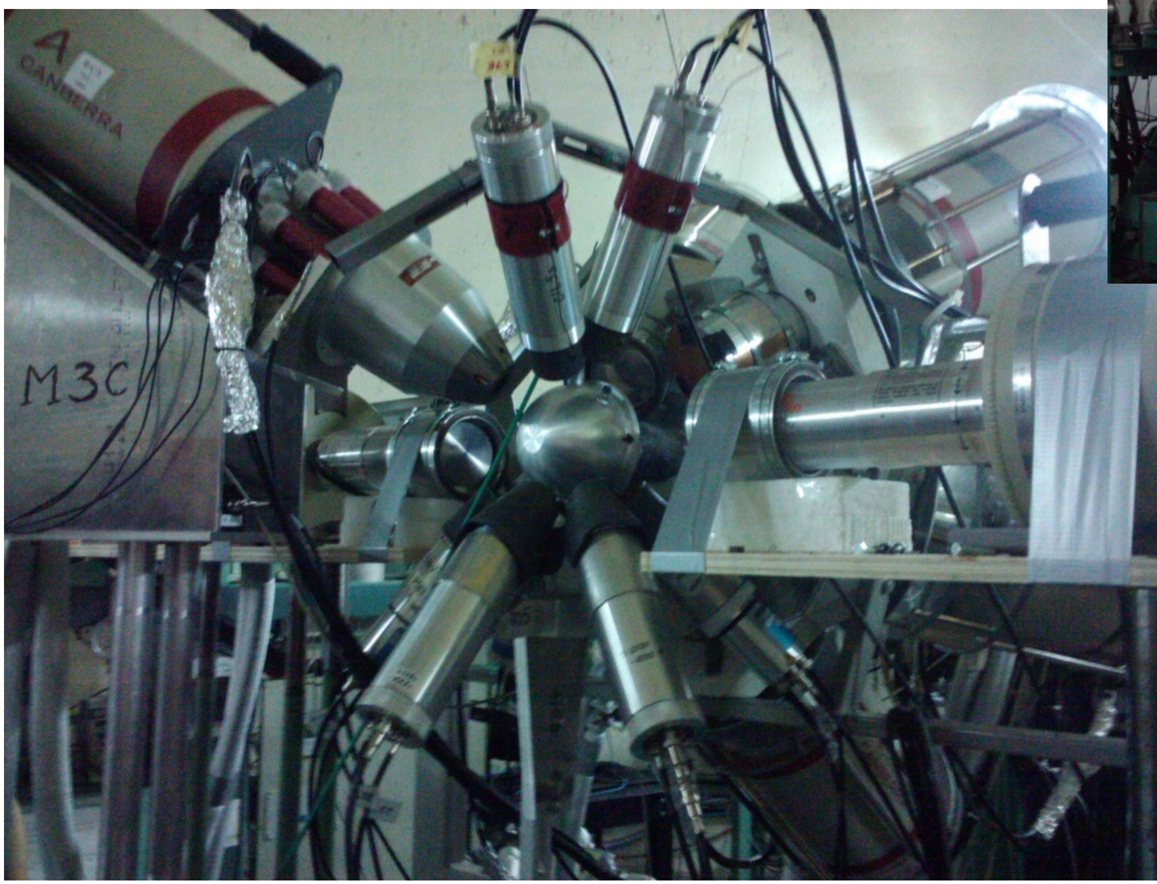
Experiment

50mg/cm^2 $Ta_2{}^{18}O$ Enriched foil
^{18}O Beam from Bucharest Tandem
(~20pnA)



Array 8 HPGe (unsuppressed) and 7 $LaBr_3$:Ce detectors

-3 (2"x2") cylindrical
-2 (1"x1.5") conical
-2 (1.5"x1.5") cylindrical

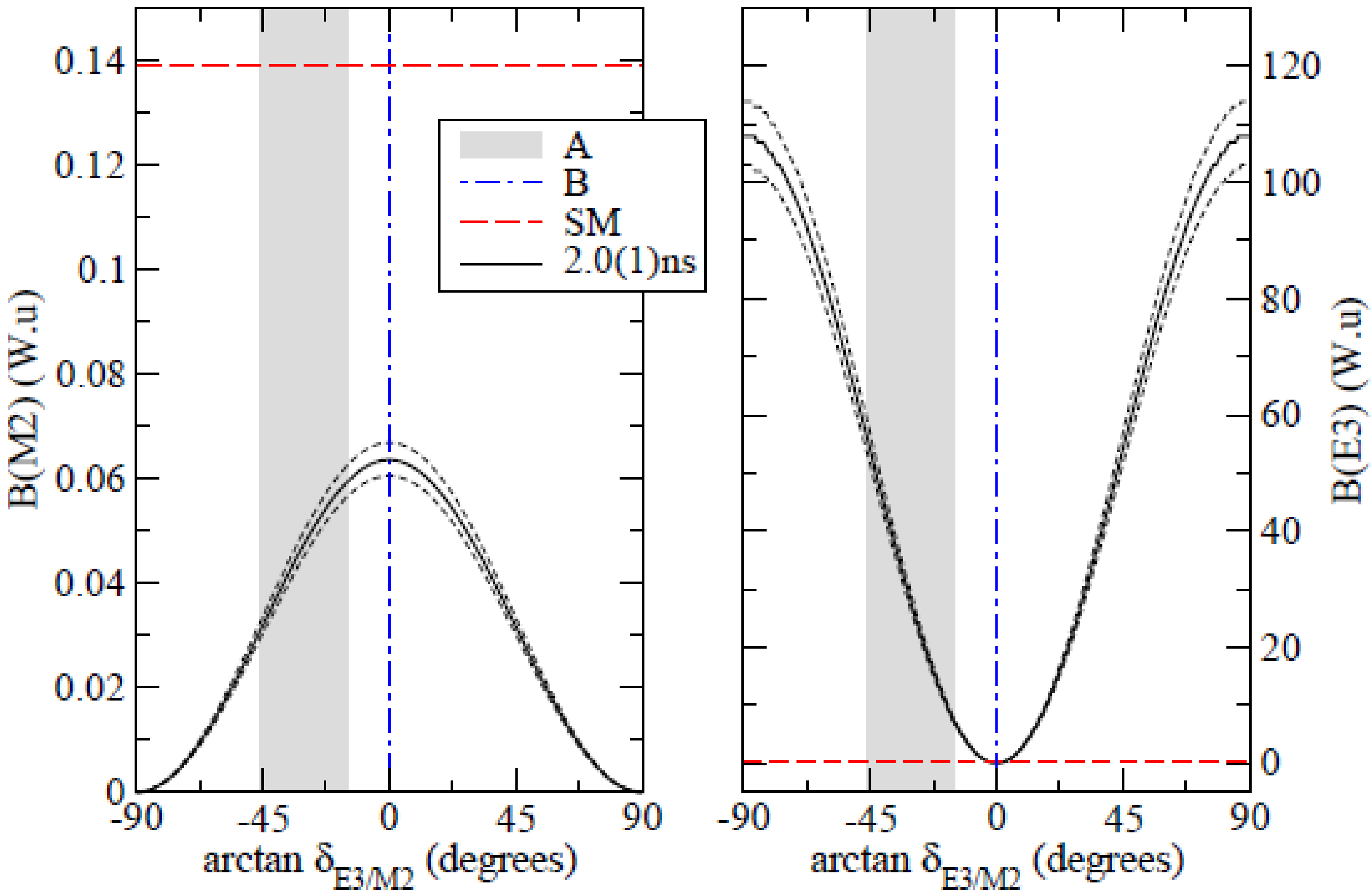
Abstract

The half-life of the $I^{\pi} = 4^{-}$ intruder state in ^{34}P has been measured as $t_{1/2} = 2.0(1)$ ns using γ-ray coincidence, fast-timing techniques with the Bucharest HPGe and $LaBr_3$:Ce detector array. Excited states in ^{34}P were populated using the $^{18}O(^{18}O,pn)^{34}P$ fusion-evaporation reaction at a beam

- **Theoretical predictions suggest**
  - **2^{+} state based primarily on $[\pi 2s_{1/2} \times (\nu 1d_{3/2})^{-1}]$ configuration and**
  - **4^{-} state based primarily on $[\pi 2s_{1/2} \times \nu 1f_{7/2}]$ configuration.**

- **Thus expect transition to go mainly via $f_{7/2}$ -to- $d_{3/2}$, M2 transition.**

- **Different admixtures in 2^{+} and 4^{-} states allow mixed M2/E3 transition**

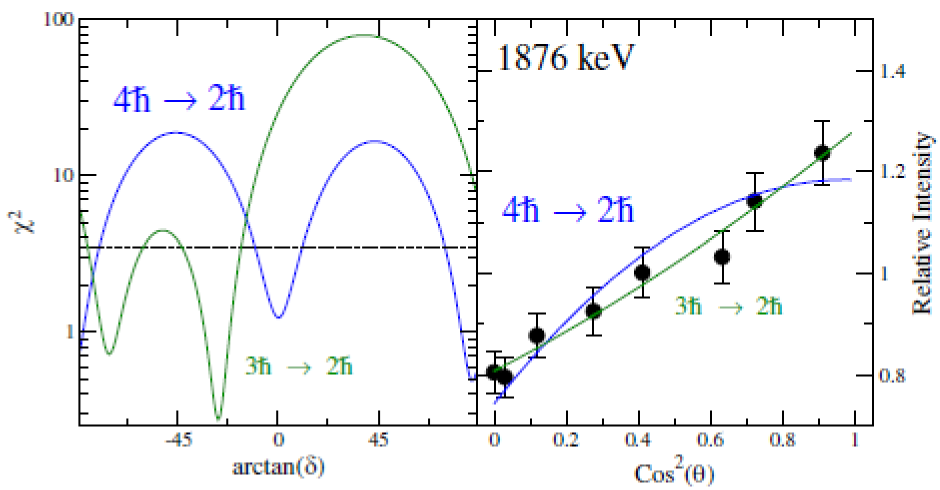


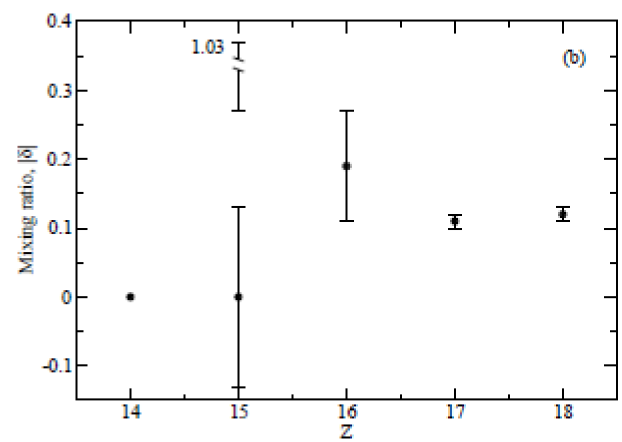
[8] P.C. Bender *et al.*, in preparation (unpublished).

http://etd.lib.fsu.edu/theses/available/etd-08032011-134836/

Table 6.13: Summary of experimental data on ^{34}P. The B values are for the indicated multipolarity λ. In some cases more than one possible spin in compared to theory.

E_x (keV)	E_γ (keV)	J_n^π initial	J_n^π final	Branch (%)	Mean τ (ps)	a_2	a_4	arctan(δ) (deg.)	λ	B value (W.u.)	WBP-a (W.u.)	SDPF-s (W.u.)
429	429	2_1^+	1_1^+	100	1.9(+9/-5))	-0.087	0.021	-5	M1	0.21(+8/-7)	0.33	
1608	1179	1_2^+	2_1^+	66	0.75(+65/-20))	-0.033	0.005		M1	0.017(+6/-7)	0.005	
	1607		1_1^+	34					M1	.004(+1/-2))	0.001	
2229	621	2_1^-	1_2^+	30	> 2.8	-0.121	0.064	-3	E1	$< 4 \cdot 10^{-4}$		
	1800		2_1^+	44					E1	$< 2.5 \cdot 10^{-5}$		
	2229		1_1^+	26					E1	$< 8 \cdot 10^{-6}$		
2305	1876	4_1^-	2_1^+	100	2900(290)	0.319	0.015	0	M2	0.064(6)	0.15	
2320	1891	3_1^-	2_1^+	100	> 10	-0.146	0.032	-3	E1	$< 1.5 \cdot 10^{-4}$		





Theory

Results

wbp-a

sdpf-m

sdpf-mw

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Cross-shell excitations in ^{30}Al and ^{30}Si at high spin

D. Steppenbeck [a,*], A.N. Deacon [a], S.J. Freeman [a], R.V.F. Janssens [b], M.P. Carpenter [b], C.R. Hoffman [c,1], B.P. Kay [a,1], T. Lauritsen [b], C.J. Lister [b], D. O'Donnell [d,2], J. Ollier [d,2], D. Seweryniak [b], J.F. Smith [d], K.-M. Spohr [d], S.L. Tabor [c], V. Tripathi [c], P.T. Wady [d], S. Zhu [b]

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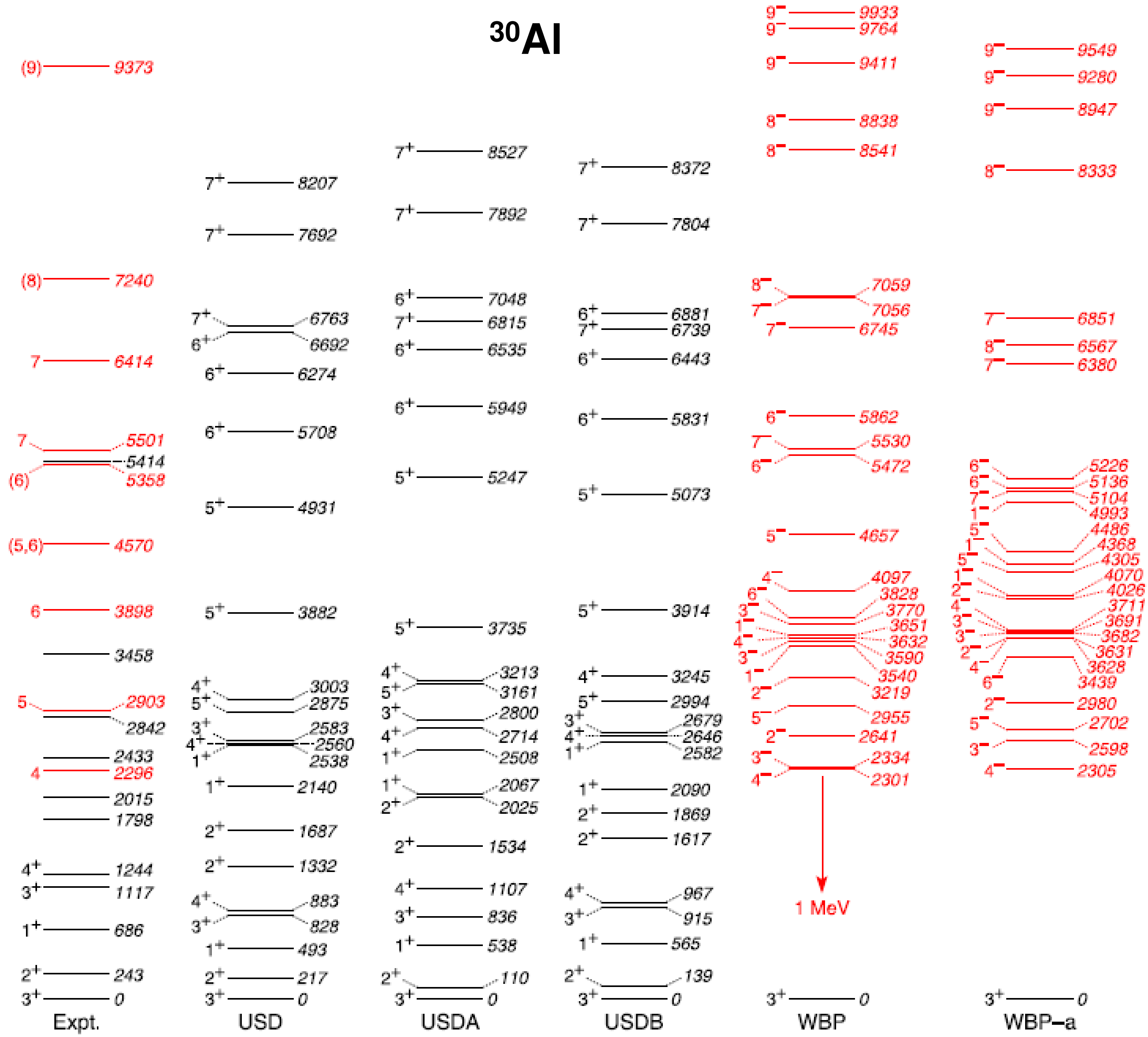
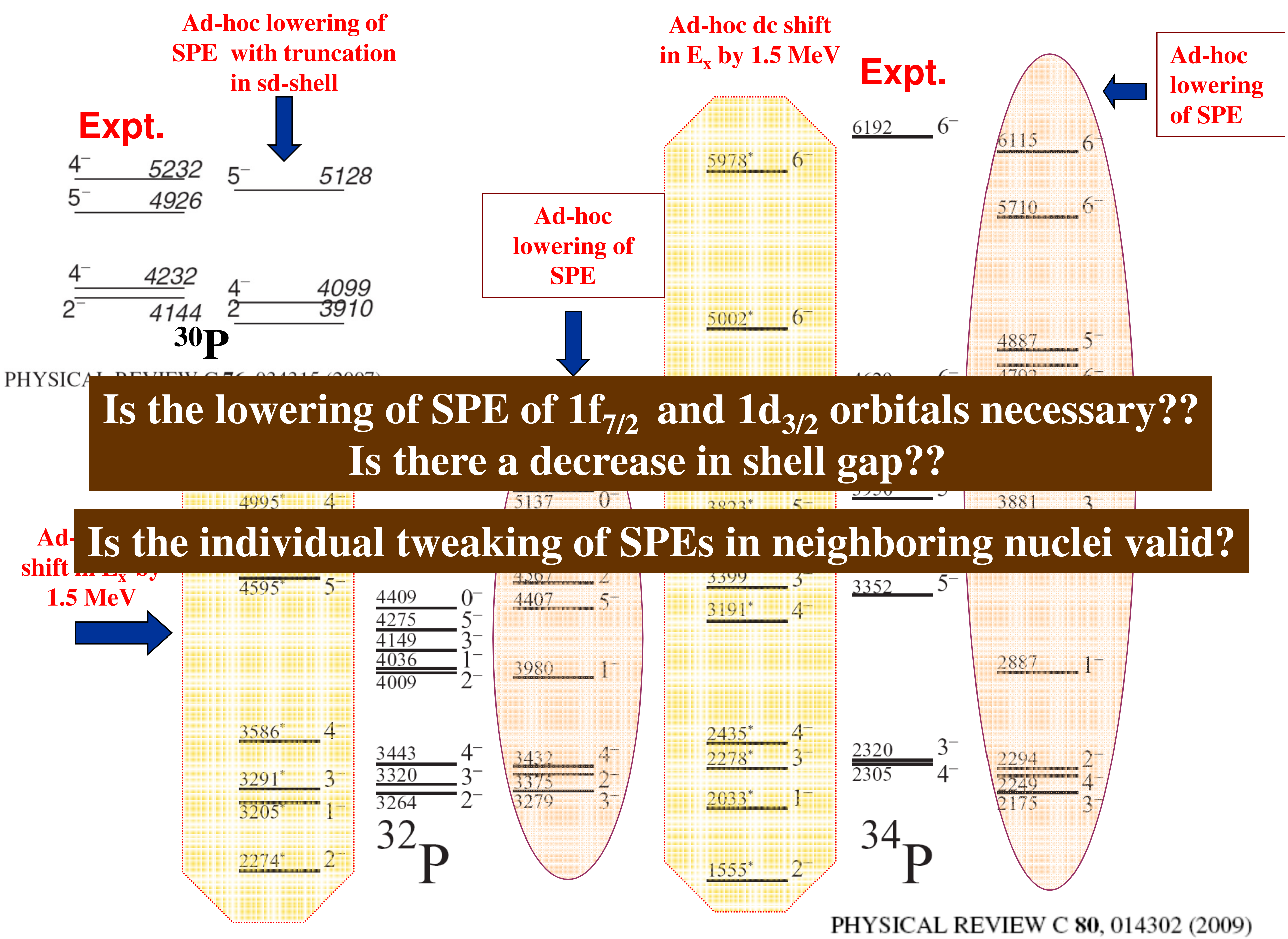

30Al
Expt.
(9) 9373
(8) 7240
7 6414
7 5501
5414
(6) 5358
(5,6) 4570
6 3898
3458
5 2903
2842
2433
4 2296
2015
1798
4+ 1244
3+ 1117
1+ 686
2+ 243
3+ 0
USD
7+ 8207
7+ 7692
7+ 6763
6+ 6692
6+ 6274
6+ 5708
5+ 4931
5+ 3882
4+ 3003
5+ 2875
3+ 2583
4+ 2560
1+ 2538
1+ 2140
2+ 1687
2+ 1332
4+ 883
3+ 828
1+ 493
2+ 217
3+ 0
USDA
7+ 8527
7+ 7892
6+ 7048
7+ 6815
6+ 6535
6+ 5949
5+ 5247
5+ 3735
4+ 3213
5+ 3161
3+ 2800
4+ 2714
1+ 2508
1+ 2067
2+ 2025
2+ 1534
4+ 1107
3+ 836
1+ 538
2+ 110
3+ 0
USDB
7+ 8372
7+ 7804
6+ 6881
7+ 6739
6+ 6443
6+ 5831
5+ 5073
5+ 3914
4+ 3245
5+ 2994
3+ 2679
4+ 2646
1+ 2582
1+ 2090
2+ 1869
2+ 1617
4+ 967
3+ 915
1+ 565
2+ 139
3+ 0
WBP
9− 9933
9− 9764
9− 9411
8− 8838
8− 8541
8− 7059
7− 7056
7− 6745
6− 5862
7− 5530
6− 5472
5− 4657
4− 4097
6− 3828
3− 3770
1− 3651
4− 3632
3− 3590
1− 3540
2− 3219
5− 2955
2− 2641
3− 2334
4− 2301
1 MeV
3+ 0
WBP−a
9− 9549
9− 9280
9− 8947
8− 8333
7− 6851
8− 6567
7− 6380
6− 5226
6− 5136
7− 5104
1− 4993
5− 4486
1− 4368
5− 4305
1− 4070
2− 4026
4− 3711
3− 3691
3− 3682
2− 3631
4− 3628
6− 3439
2− 2980
5− 2702
3− 2598
4− 2305
3+ 0

Such observations imply that the energies of the negative parity states are, to a good approximation, simple reduced by a common quantity with increasing neutron number, this may be naively interpreted as a reduction in the magnitude of the energy gap between the neutron Fermi surface and the fp shell.



Is the lowering of SPE of $1f_{7/2}$ and $1d_{3/2}$ orbitals necessary??
Is there a decrease in shell gap??

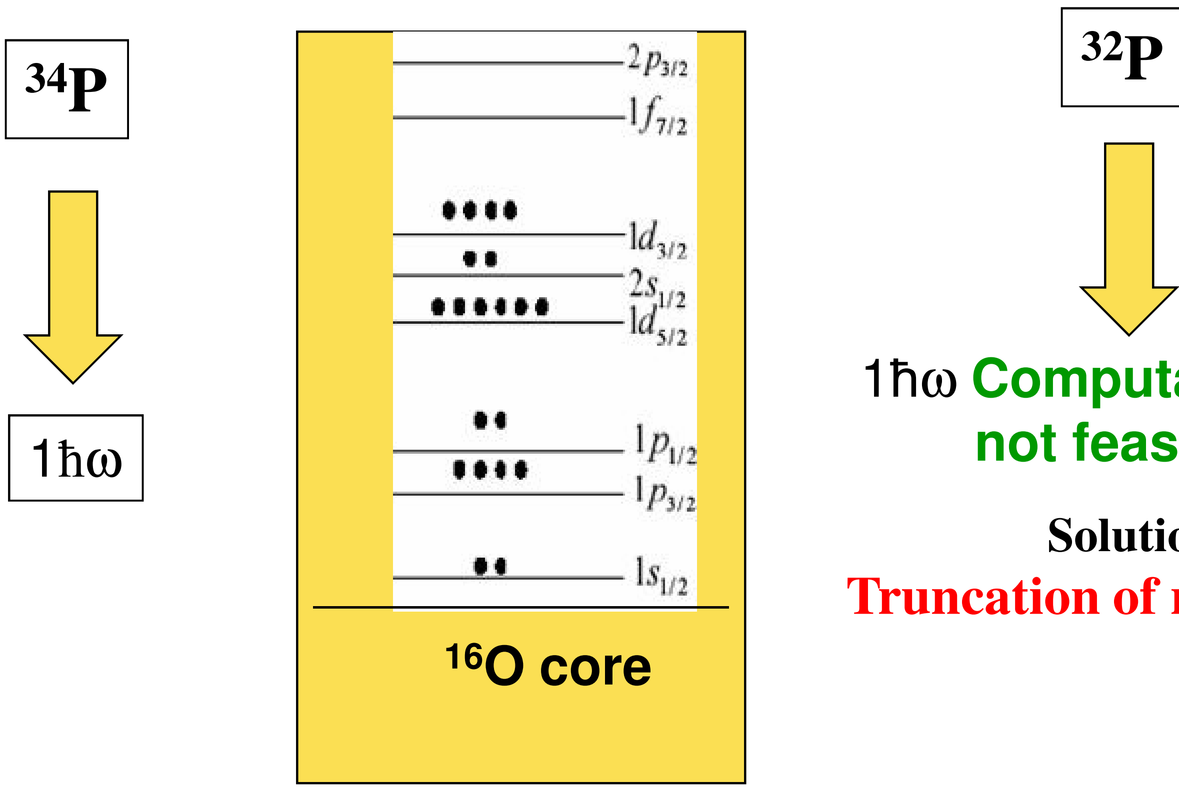
Is the individual tweaking of SPEs in neighboring nuclei valid?

Shell Model calculations using Nushell Code

Interaction: *sdpfmw*

For positive parity states:
Calculations with full *sd* shell as valence space outside ^{16}O core

For negative parity and high-lying positive parity states:
Desired valence space: Full *sdpf* outside ^{16}O core.



1ħω **Computationally not feasible!**

Solution:
Truncation of model space

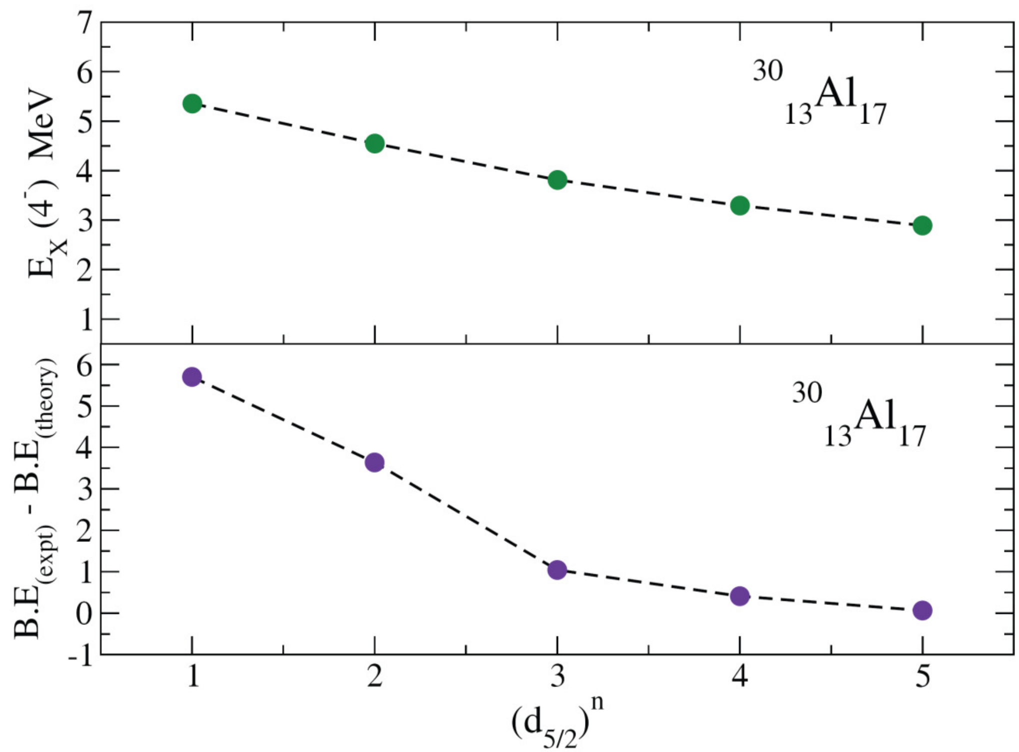
Possible reasons behind the need to lower SPEs

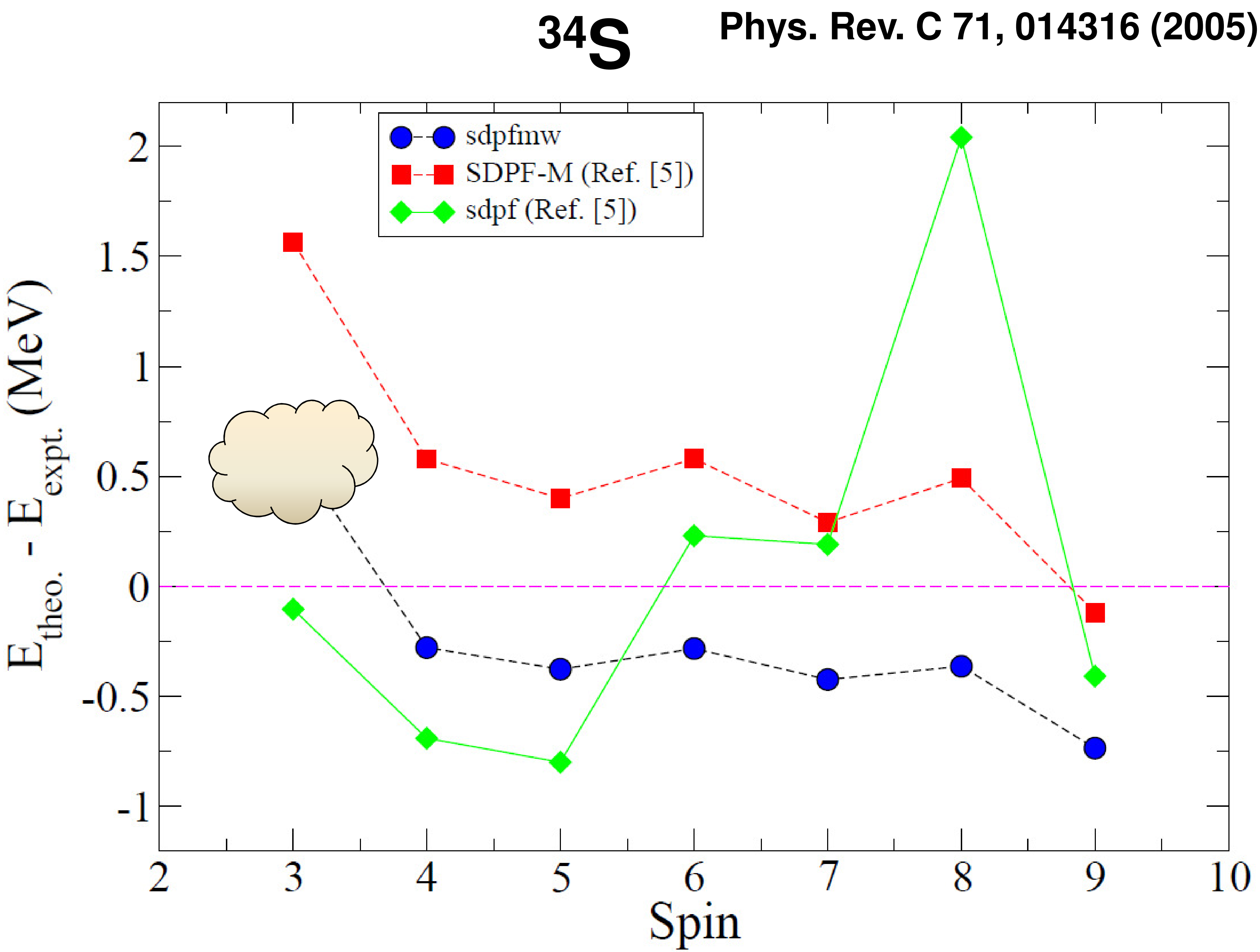
- Inappropriate choice of Two-Body-Matrix-Elements.
  - The TBME used may not be optimized for this region.

Warburton *et al*. (Phys. Rev. C 41, 1147 (1990)) have developed an interaction which

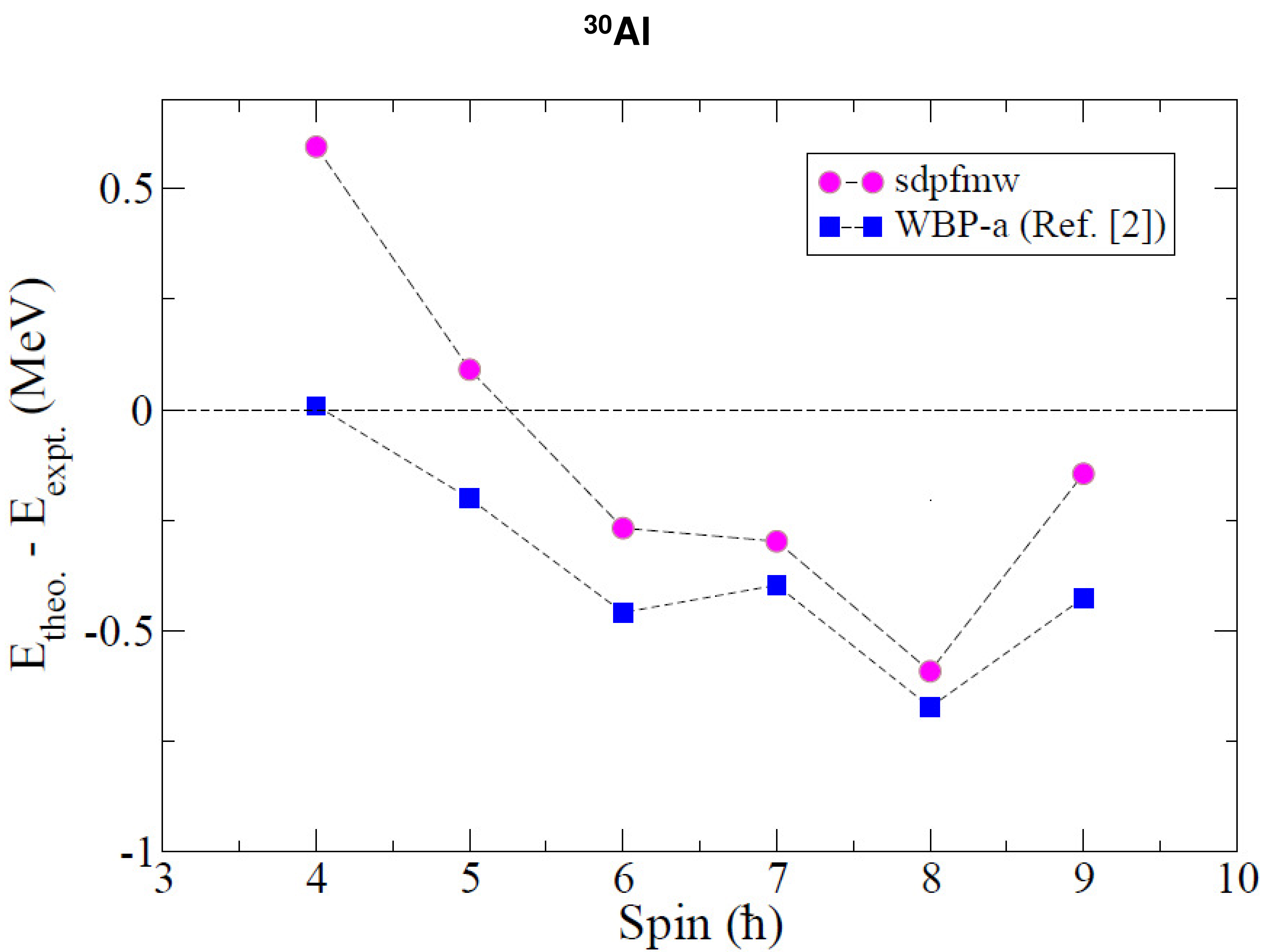
- Optimized for A = 29 - 44
- Includes the necessary ingredients for the cross-shell terms

- Truncation of the model space
  - The truncation of the model space renders the ground state less bound, resulting in the excitation energies occurring at higher values compared to their experimental counterpart





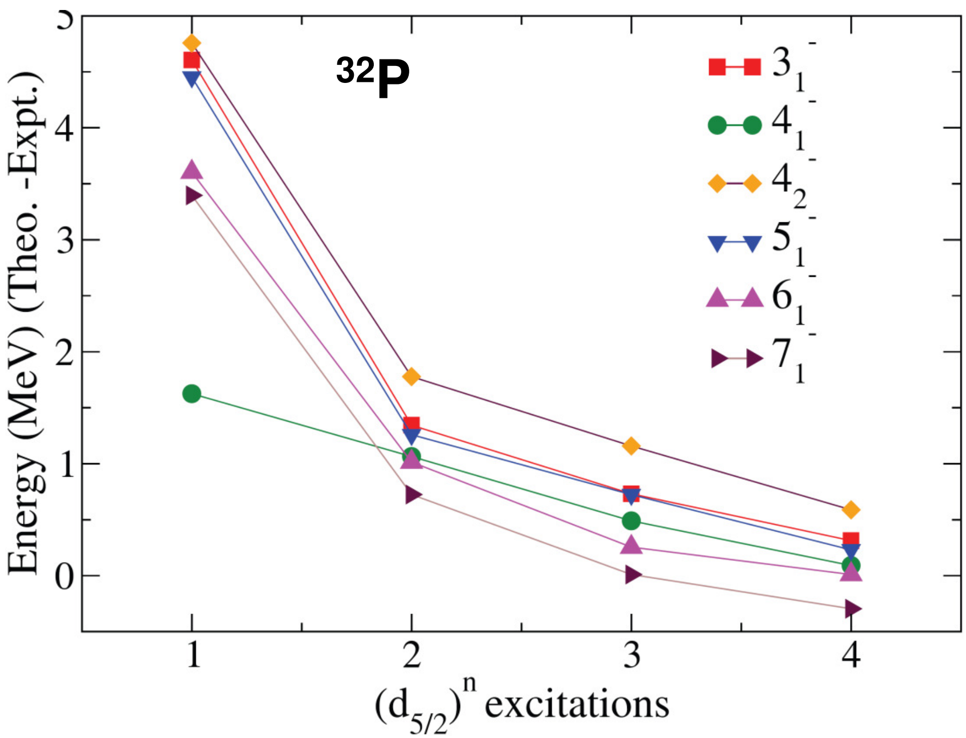
34S
Phys. Rev. C 71, 014316 (2005)
sdpfmw
SDPF-M (Ref. [5])
sdpf (Ref. [5])
E theo. - E expt. (MeV)
Spin
2
1.5
1
0.5
0
-0.5
-1
2
3
4
5
6
7
8
9
10

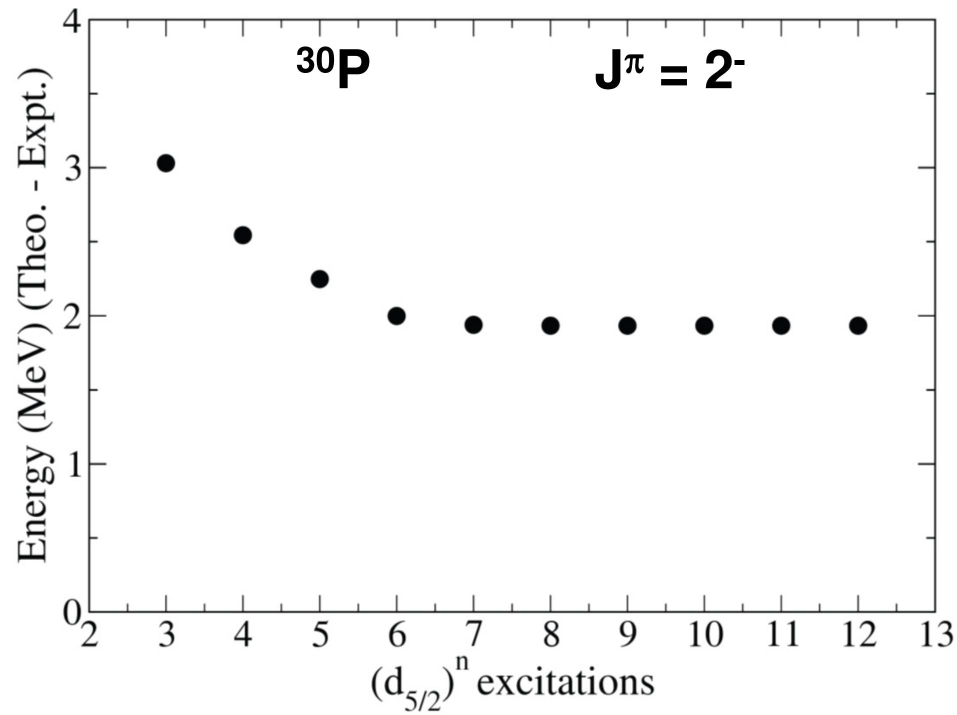


30Al
sdpfmw
WBP-a (Ref. [2])
0.5
0
-0.5
-1
3
4
5
6
7
8
9
10
Spin (ħ)
E theo. - E expt. (MeV)

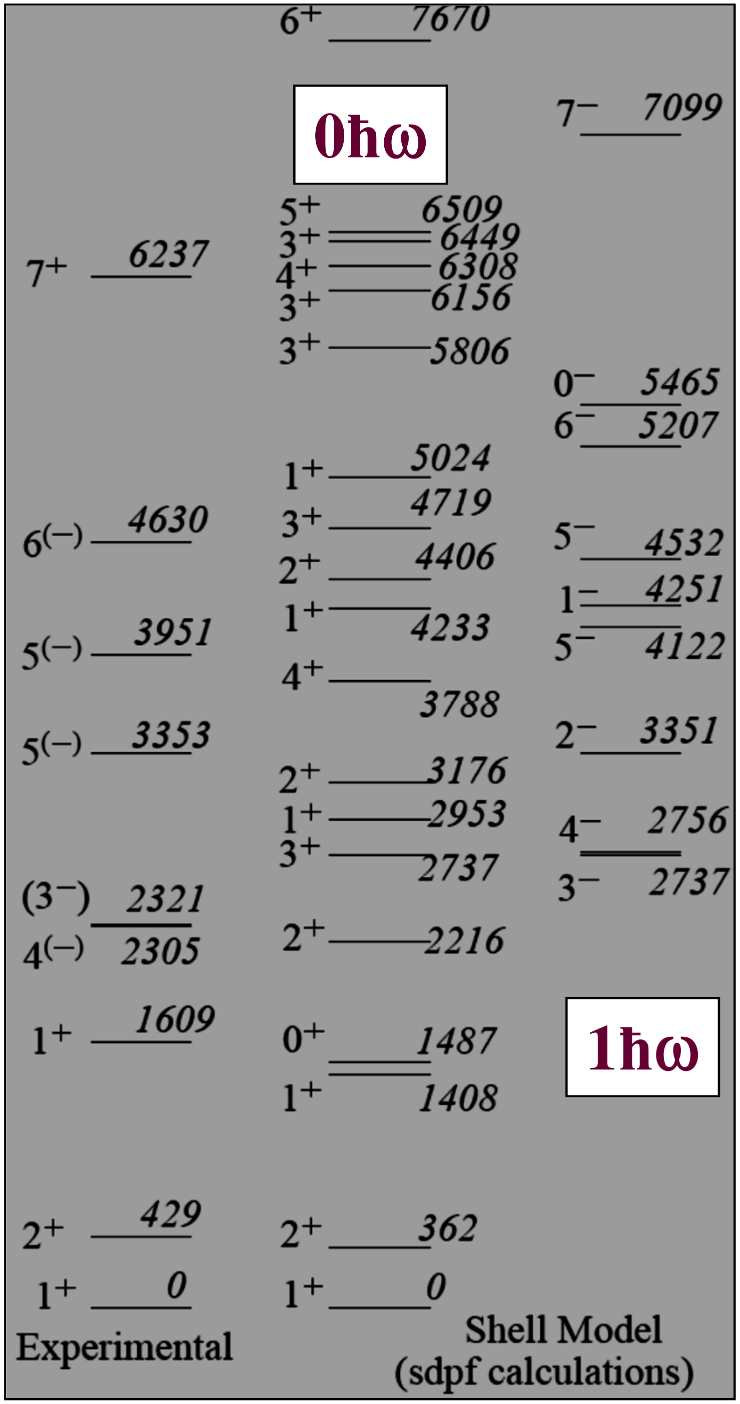
Sdpfmw interaction

No need for lowering SPE of $f_{7/2}$ or $p_{3/2}$





Plot of the difference between experimental and shell model predicted excitation energy of the negative parity states as a function of the number of particles (n) excited from $1d_{5/2}$ orbital in ^{30,32}P.

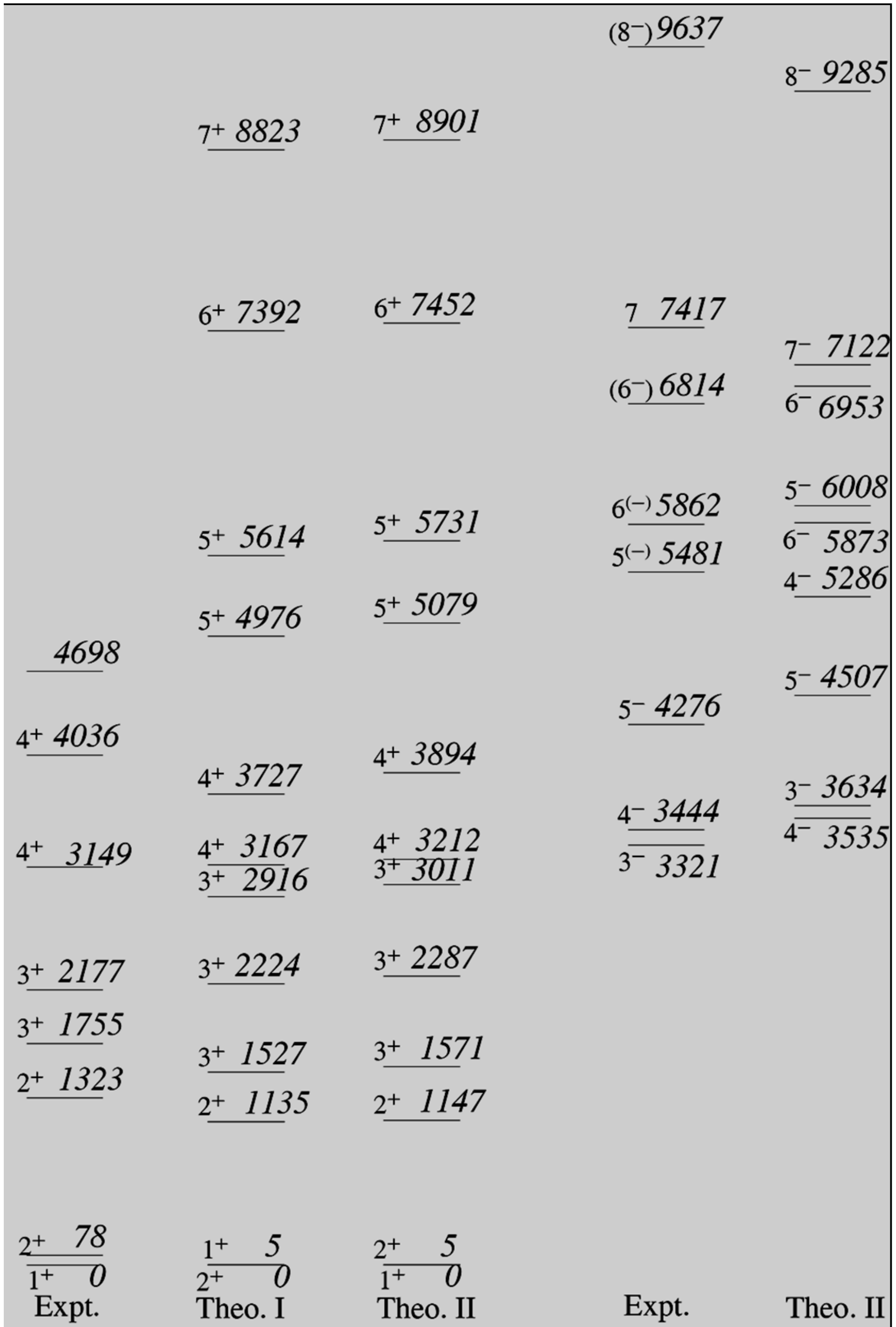


Nushell calculations
"sdpfmw interaction"

Valence space consists of
$1d_{5/2}$, $2s_{1/2}$,, $1d_{3/2}$, $1f_{7/2}$, $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$
outside ^{16}O core

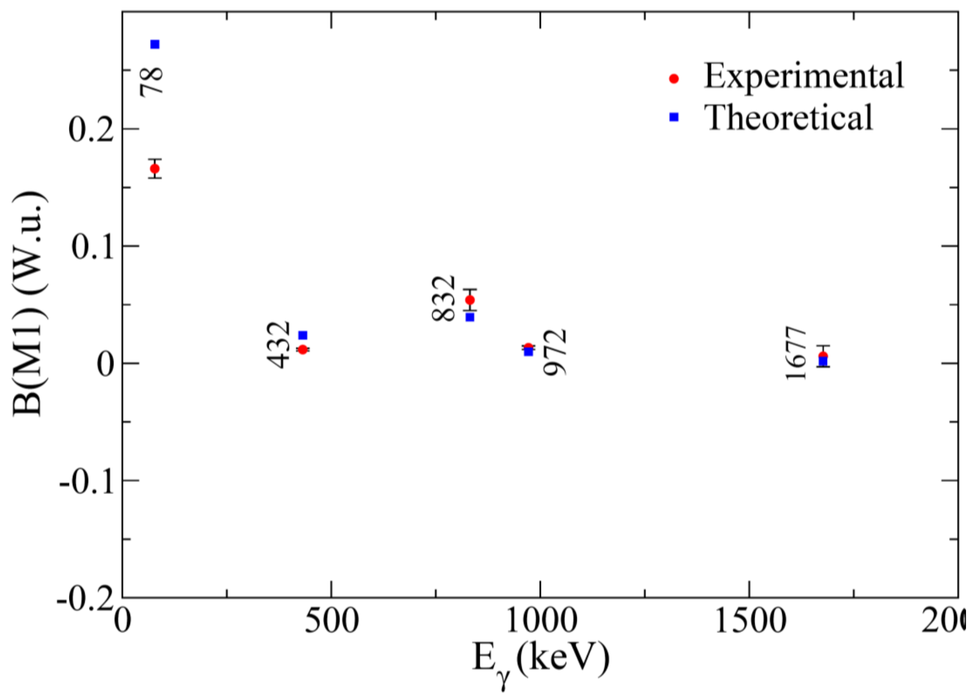
^{34}P:Comparison between theory & experiment in present work

^{32}P: Comparison between theory & experiment in present work

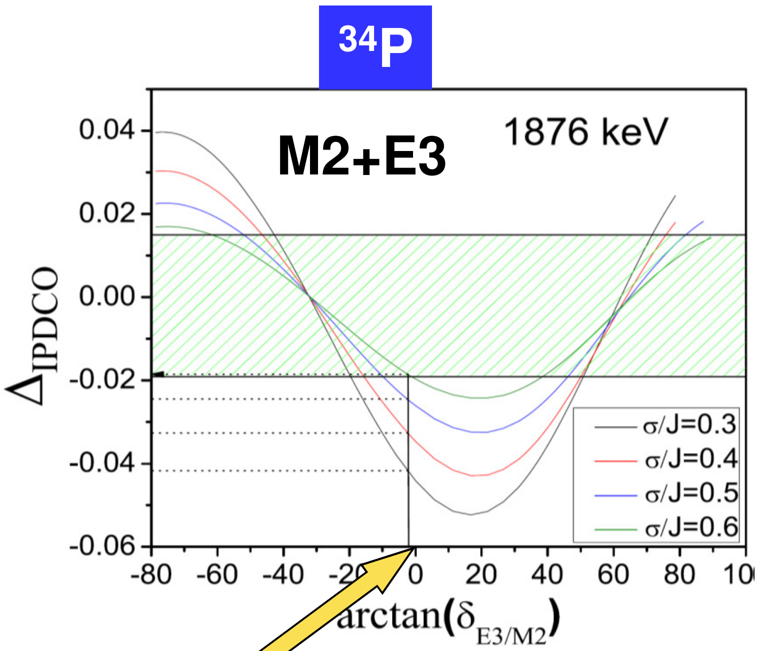


Truncation:

$d_{5/2}^{(8\text{-}12)} s_{1/2}^{(0\text{-}4)} d_{3/2}^{(0\text{-}8)} f_{7/2}^{(0\text{-}1)}$



Experimental E3/M2 mixing ratios could not be predicted by Shell model for N =19 nuclei



~zero mixing

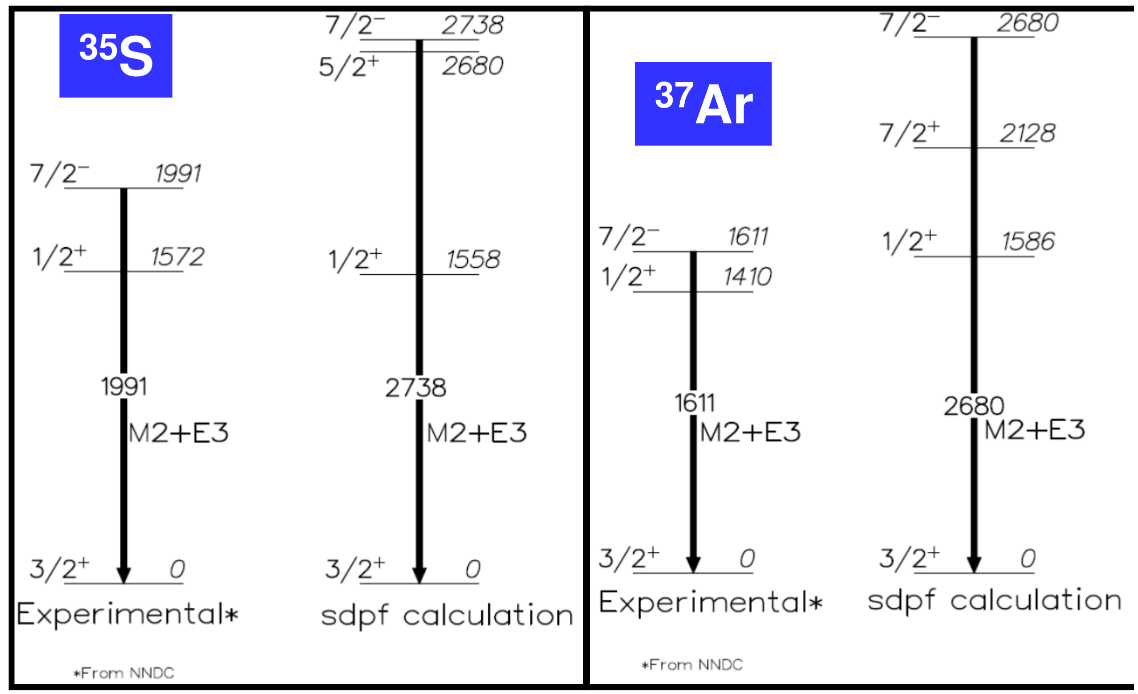


TABLE IV: Comparison between experimental and theoretical transition energies, excitation energies, mixing ratios and reduced transition probabilities in ^{35}S and ^{37}Ar.

E_γ[keV]		$E_x(J^\pi)[keV]$		τ[ns]	δ		$B(M2)$ [W.u.]		$B(E3)$ [W.u.]	
Expt.	Theo.	Expt.	Theo.	from NNDC	Expt.	Theo.	Expt.	Theo.	Expt.	Theo.
^{35}S										
1991	2738	1991	2738	1.02(5)	-0.19(8)	-0.05	0.088(5)	0.196	4.62	0.38
^{37}Ar										
1611	2680	1611	2680	4.37(9)	-0.12(1)	-0.08	0.058(13)	0.112	1.7(3)	0.50

CONCLUSION

- Use of heavy-ion fusion reaction has resulted in population of high spin states.

- The 1876-keV transition de-exciting the 2305-keV level in ^{34}P was confirmed to be a mixed transition with a plausible M2/E3 admixture.

- Shell model calculations
  - successfully reproduced low-lying positive and negative parity states.
  - No lowering of single particle energy as carried out by other workers.
  - Omission of important configurations responsible for prediction of E_x at higher energies compared to their experimental counterpart; as these get included theory approaches experiment.

- Shell model calculations reasonably successful in predicting the wave functions except in few cases, particularly the M2/E3 mixing in N=19 isotones.

- Need to perform the calculations within a larger model space and/or with an appropriate Hamiltonian (which includes microscopic intra- and inter shell interactions.)

Shell model is successful in explaining the overall Structure with certain interesting exceptions

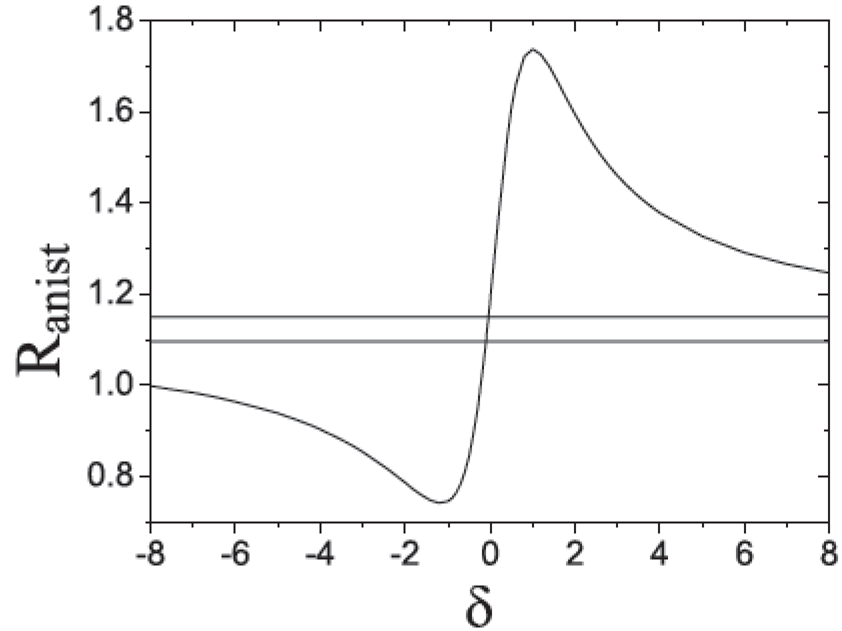


FIG. 7. Plot of the calculated R_{anist} as a function of mixing ratio for a $J = 6 \rightarrow 4$ transition. The area between the horizontal lines represent the uncertainty in the observed R_{anist} of the 2418-keV transition.