Coulomb force as a magnifying glass of shell structure in the ^{36}S - ^{36}Ca mirror nuclei

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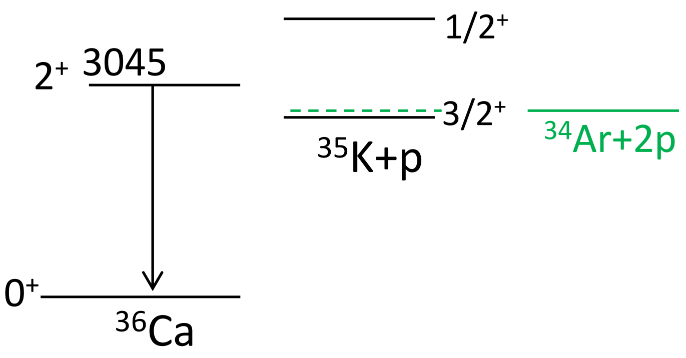
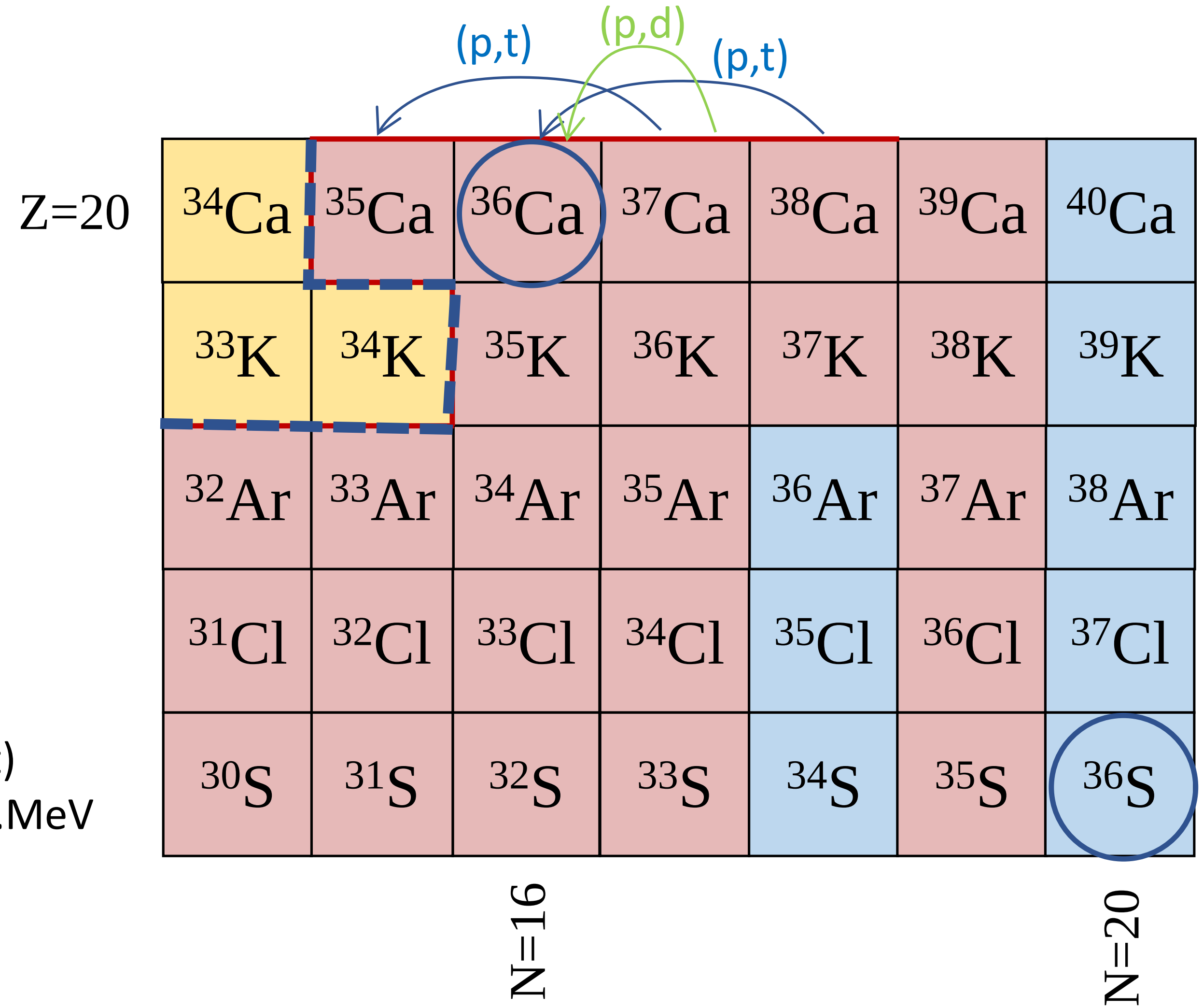
Oral contribution Colloque GANIL 2021

Studies of ^{35,36}Ca: what is known ?

^{34}Ca is unbound
Only the g.s. of ^{35}Ca and ^{36}Ca are bound
Only first excited state 2^+ of ^{36}Ca is known
It is above S_{2p} (but considered as quasi-bound as well below B_C)

B_C = 5.5 MeV





The ground and excited states of ^{35,36}Ca studied by (p,d) and (p,t)
Transfer reactions from ^{38}Ca and ^{37}Ca radioactive beams at 50 A.MeV

^{36}Ca: a new doubly magic nucleus with colossal breaking of mirror symmetry

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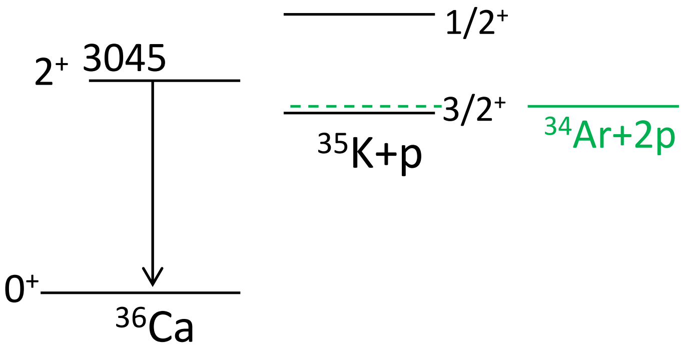
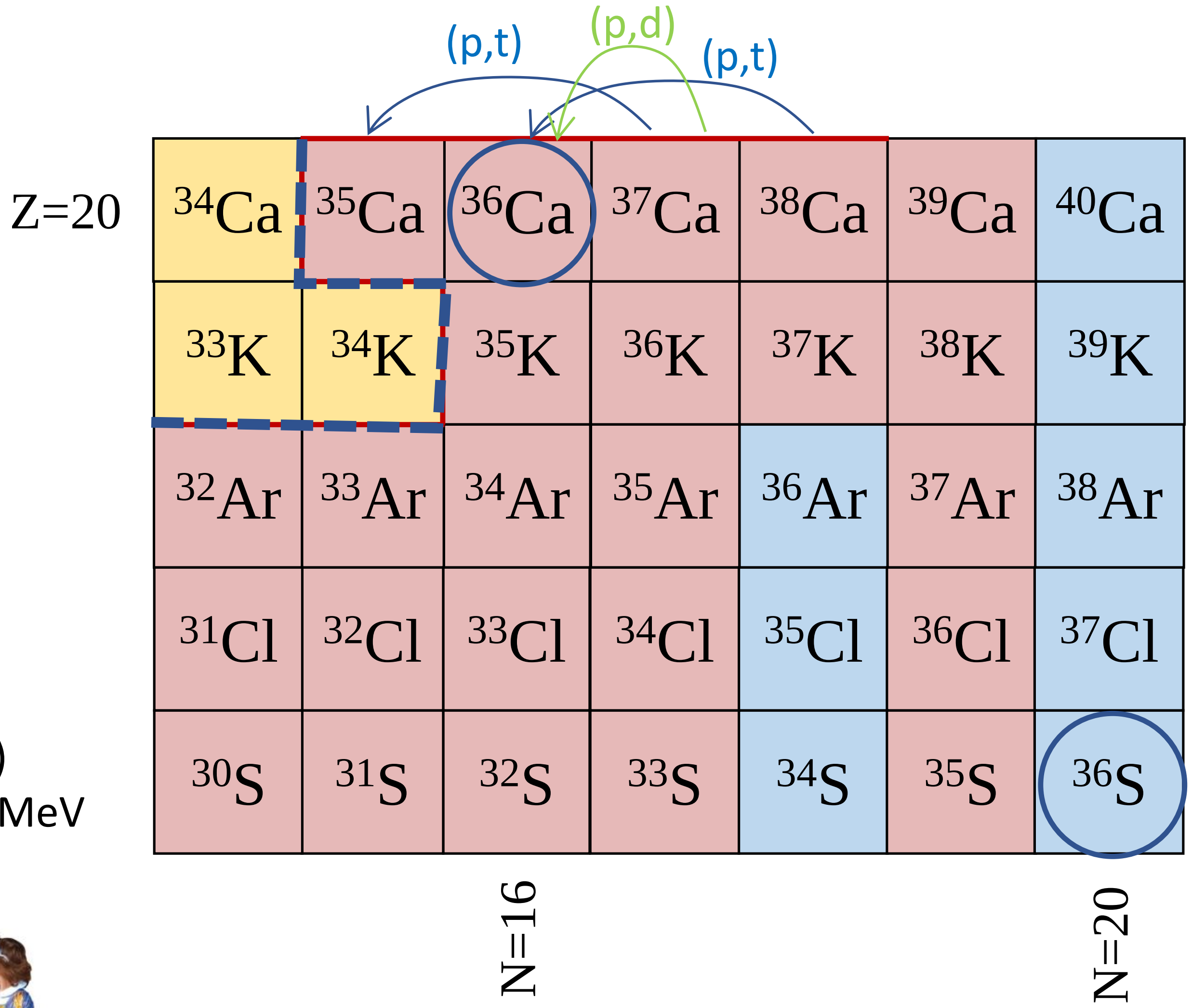




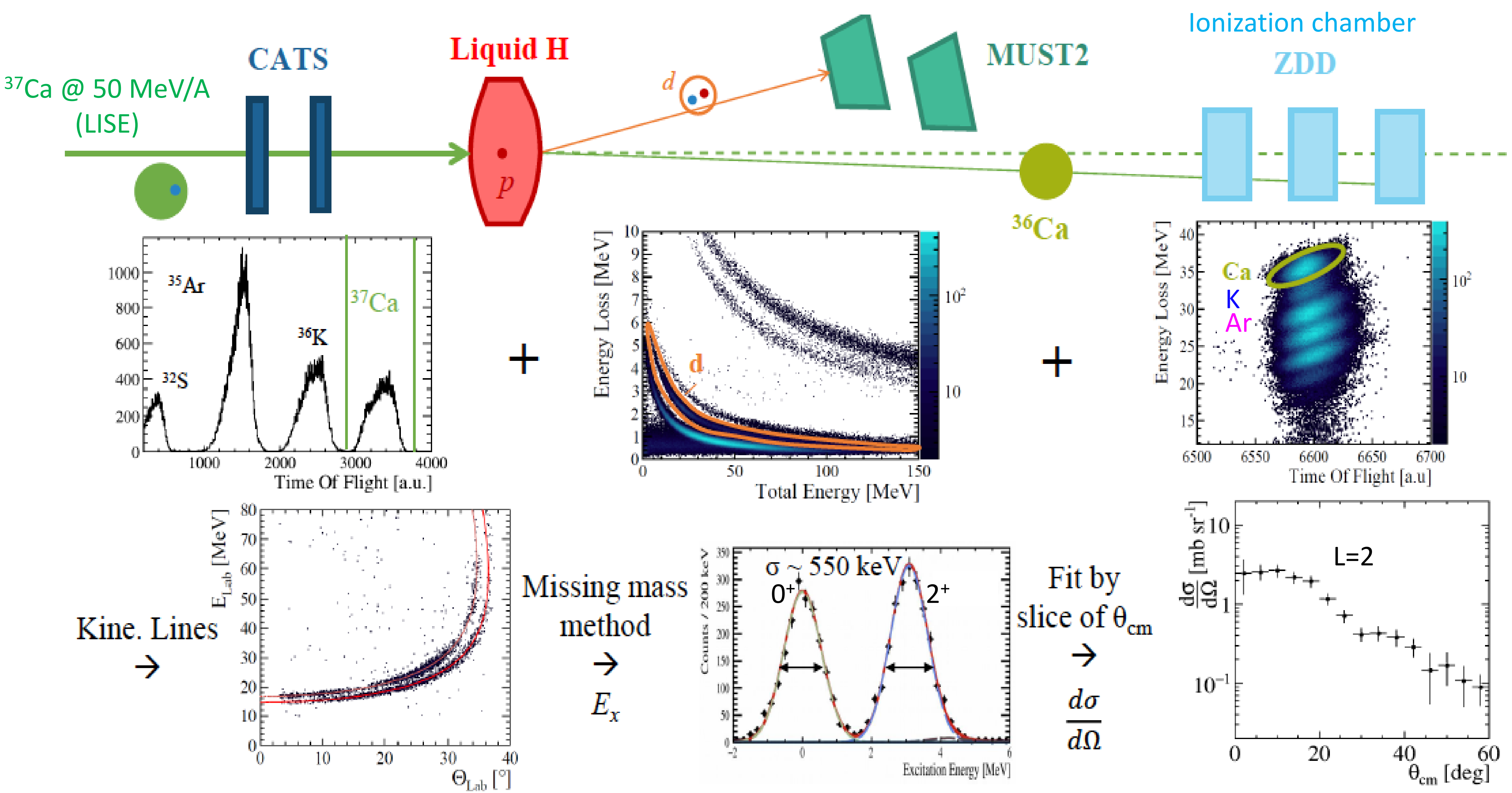
The ground and excited states of ^{35,36}Ca studied by (p,d) and (p,t)
Transfer reactions from ^{38}Ca and ^{37}Ca radioactive beams at 50 A.MeV

Layout

Experimental technique and set-up
Mirror energy difference: motivation and results
Double magicity of ^{36}Ca

Not discussed here: Astrophysical impact *L. Lalanne et al., PRC 103 (2021)*

Experimental set-up and technique

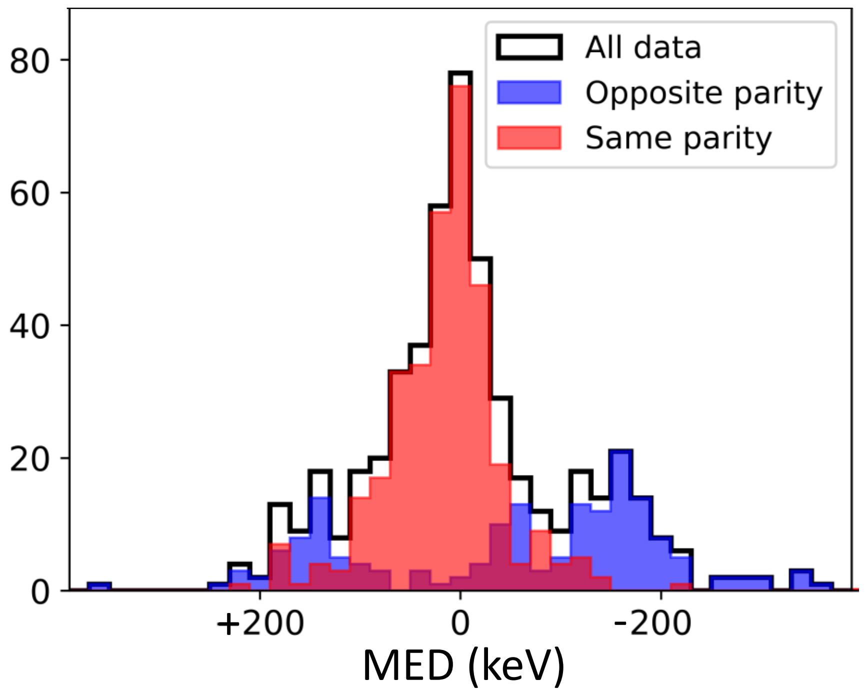


Some words about the Mirror Symmetry

Nuclear spectra between mirror nuclei usually very similar -> very small Mirror Energy difference (MED)
Except for unbound states e.g. ^{16}F - ^{16}N *I. Stefan et al. PRC 90 (2014)* where the MED is of about 650 keV.

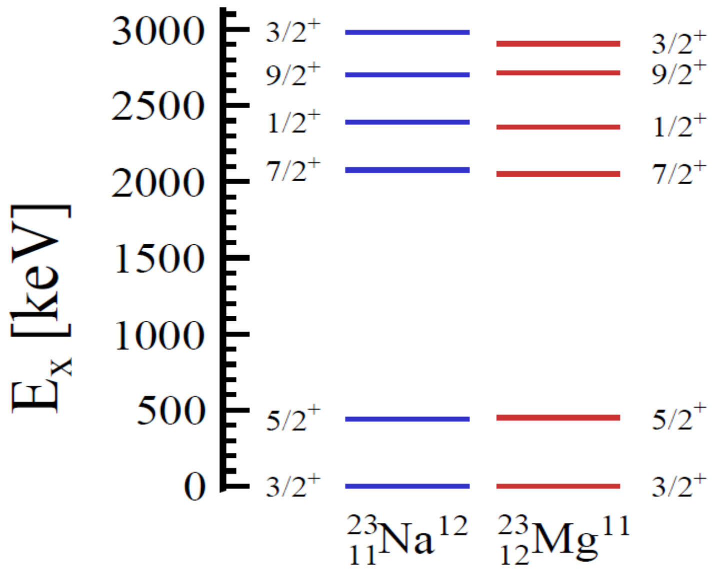
Inversion between the ground $1/2^-$ and excited state $5/2^-$ (separated by 27 keV) of A=73 mirror nuclei cannot be explained
Hoff et al. Nature 580 (2020)

Lenzi et al. PRC 102 (2020) calculated a 40-keV MED, explaining why these two levels are inverted.
Henderson and Stroberg PRC 102 (2020) concur to say that this shift has 30% chance to occur.



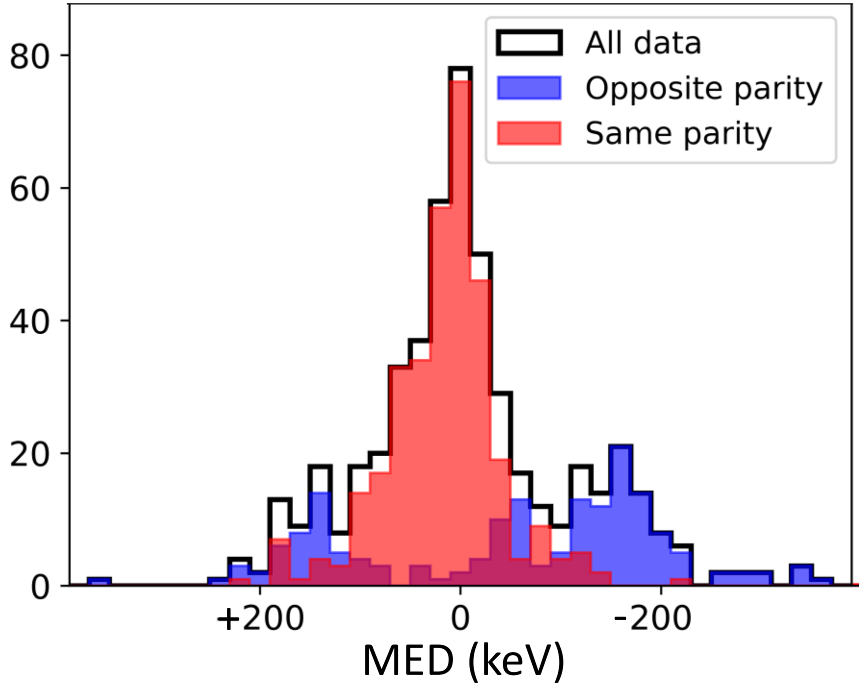
Henderson and Stroberg, PRC 102 (2020) 031303(R)

MED < 100 keV

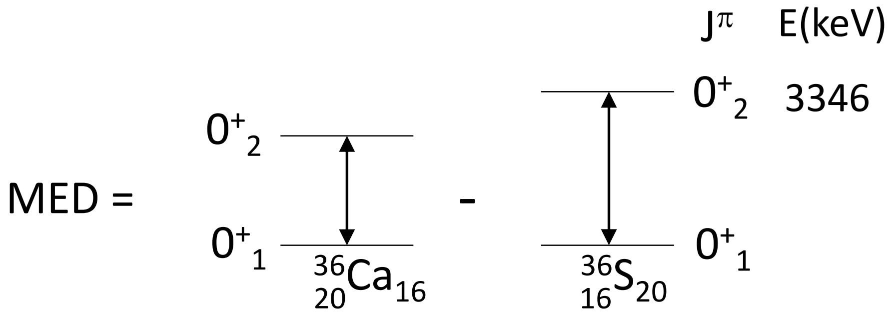


Mirror symmetry and shape coexistence

'Colossal' MED (-700 keV) predicted between the 0^+_1 and 0^+_2 states in ^{36}S - ^{36}Ca, *Valiente-Dobon et al., PRC 98 (2018).*
Due to the very different configuration of the spherical ground state and intruder 0^+_2 state

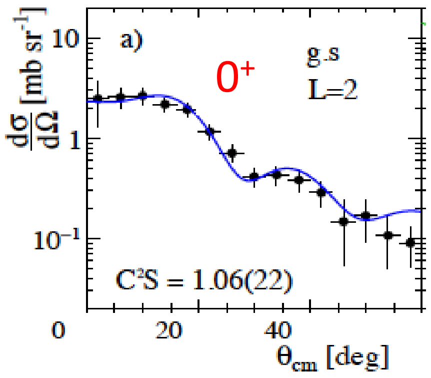


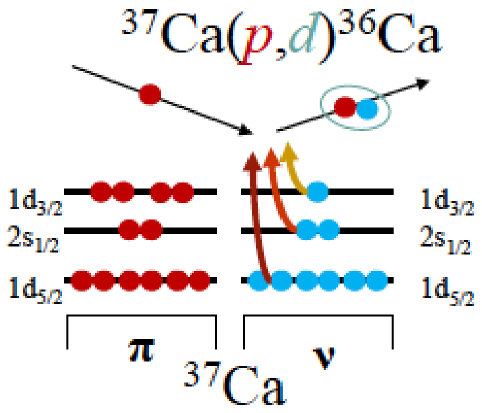
Henderson and Stroberg, PRC 102 (2020) 031303(R)

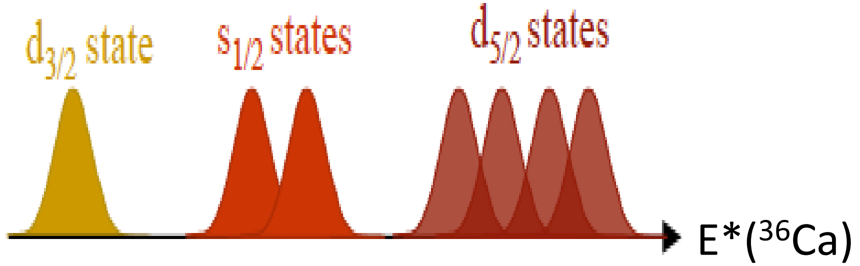


Search for 0^+_2 excited states of ^{36}Ca to see if such a 'colossal' MED exists !

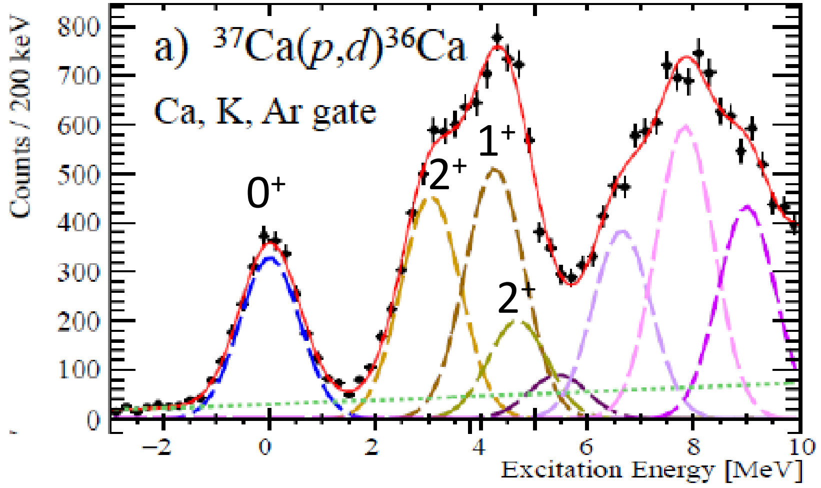
$^{37}Ca(p,d)^{36}Ca$ reaction to probe neutron-hole states







1	2	6	occupancy
0^+	$1^+,2^+$	$1^+ - 4^+$	J^π
2	0	2	L transfer



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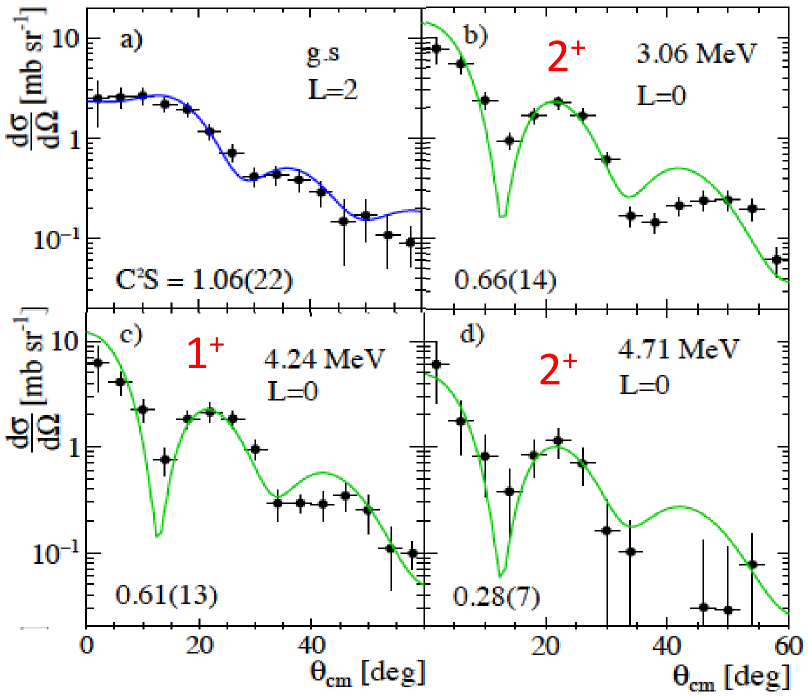

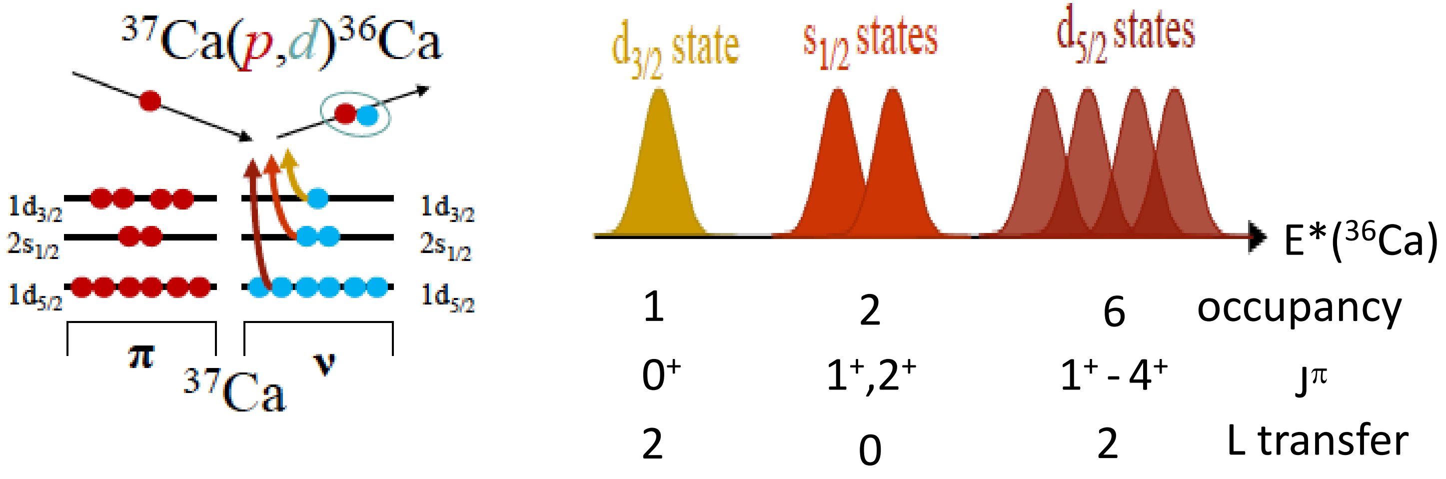

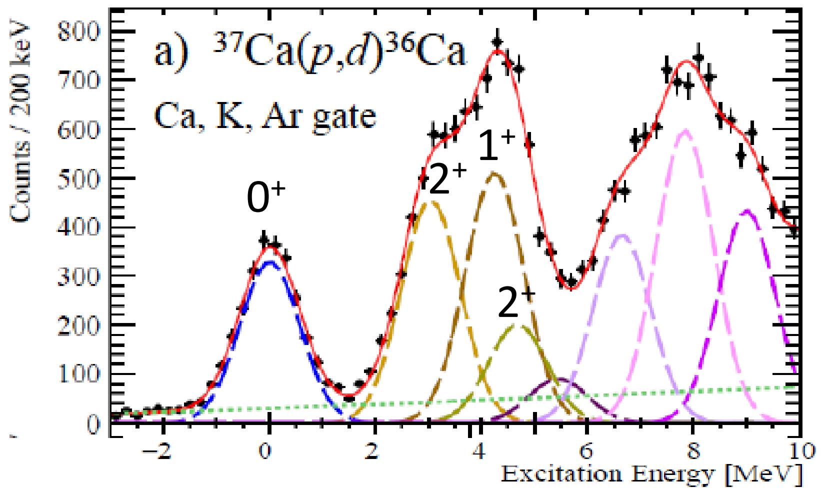

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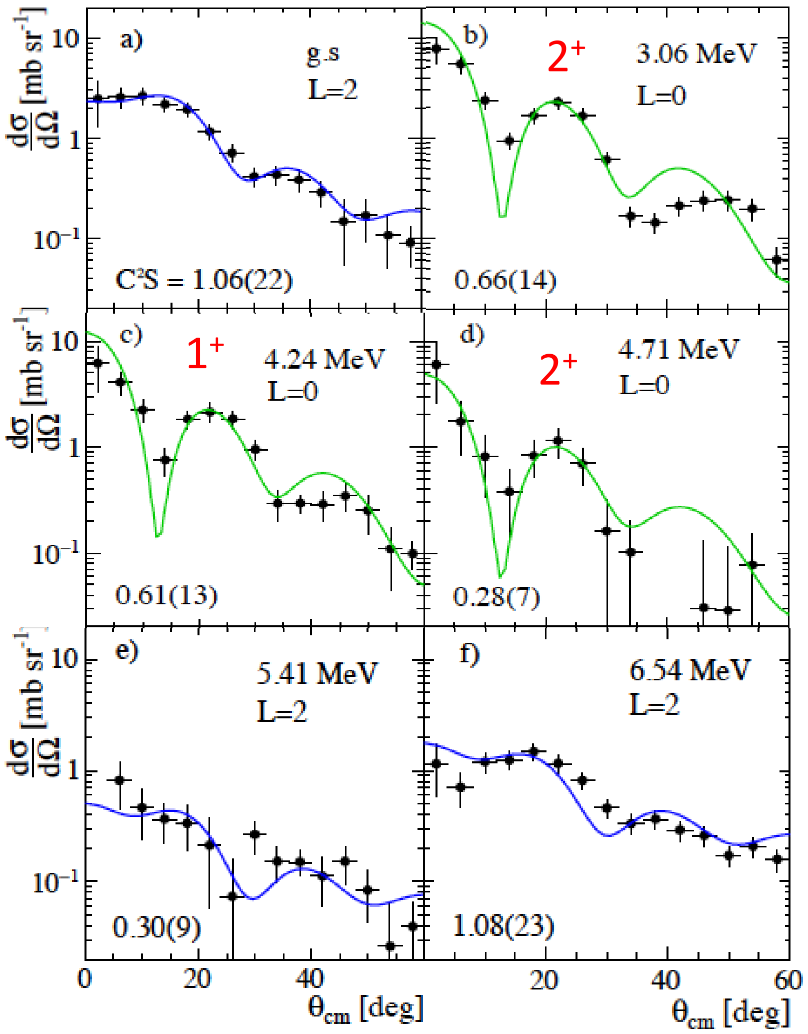

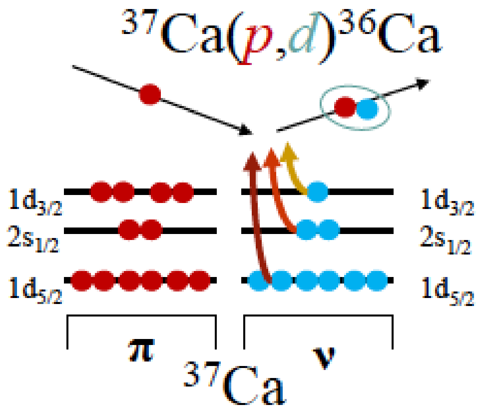

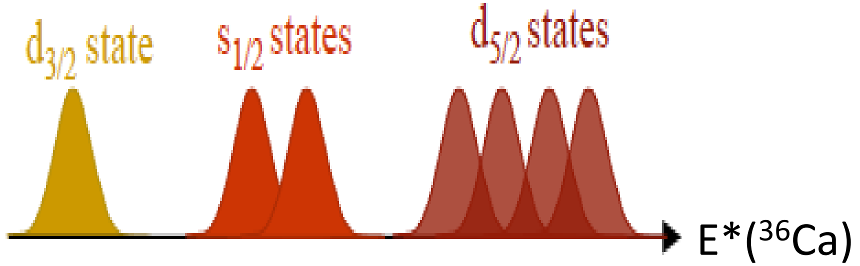

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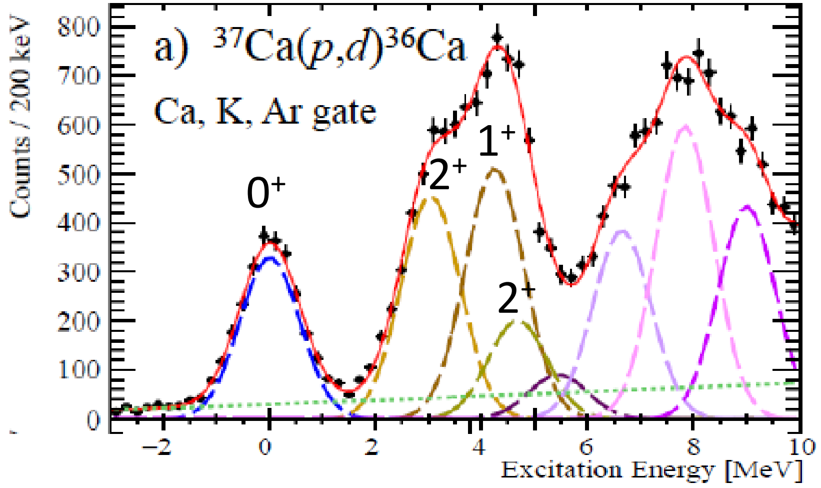
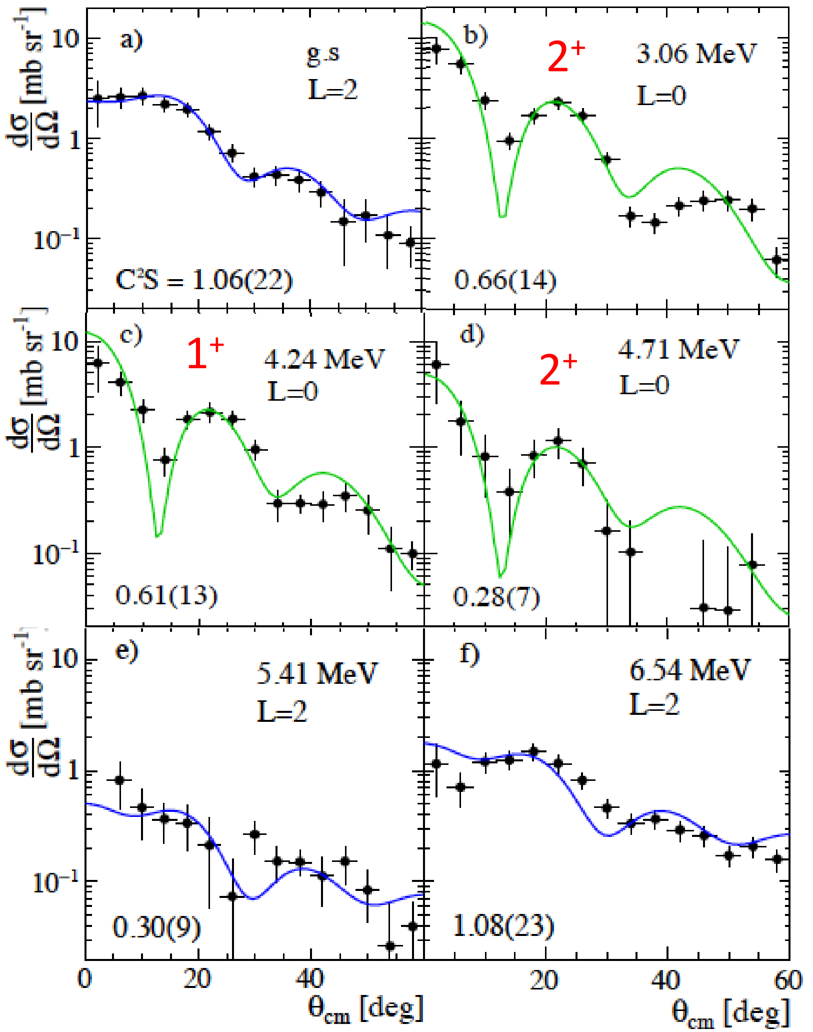
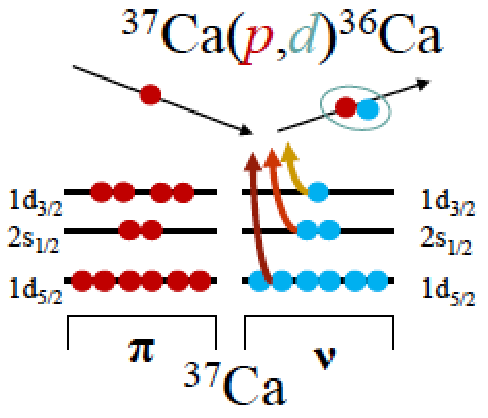
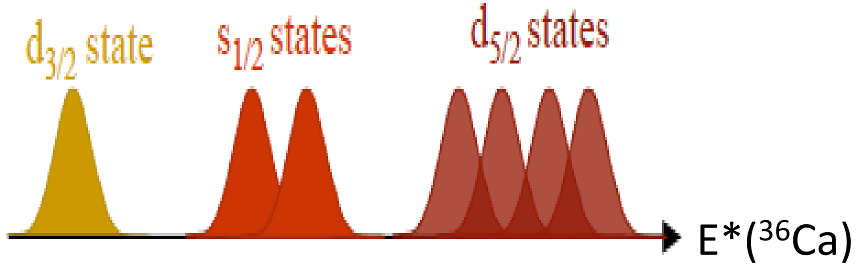


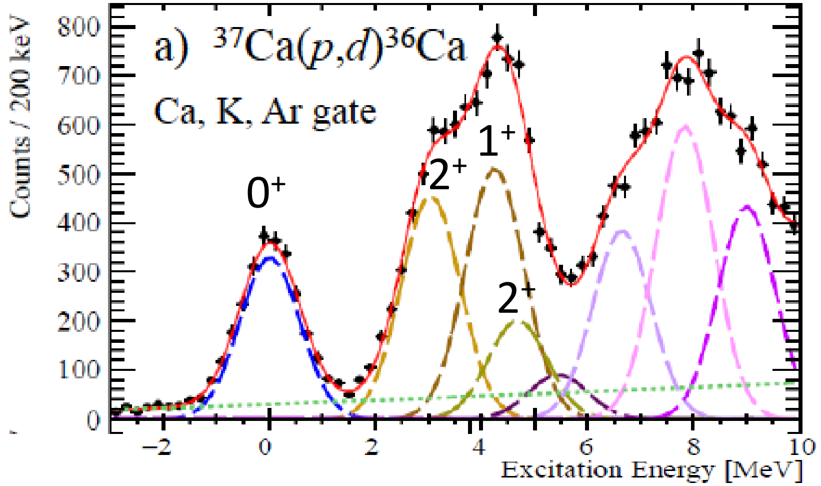
^{37}Ca(p,d)^{36}Ca reaction to probe neutron-hole states







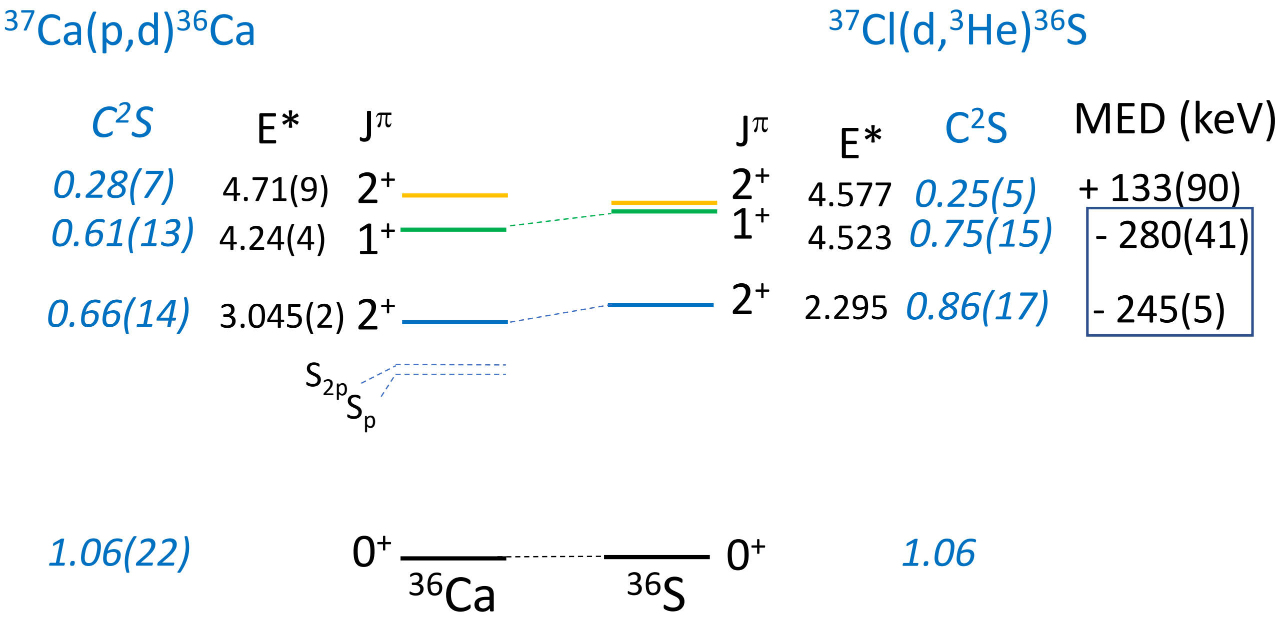
1	2	6	occupancy
1.06(22)	1.86(23)	4.38(88)	C^2S_{exp}
0^+	$1^+,2^+$	$1^+ - 4^+$	J^π
2	0	2	L transfer

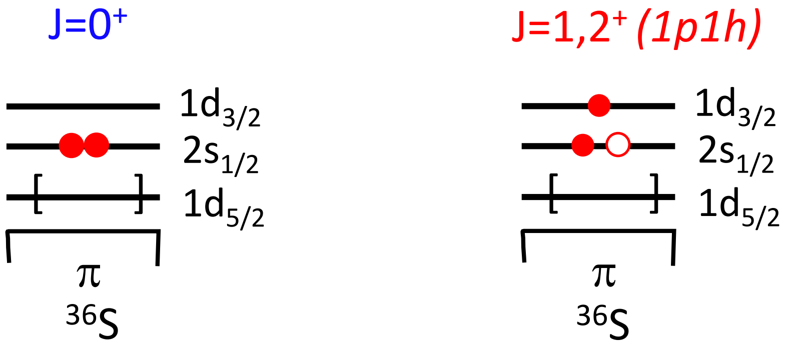


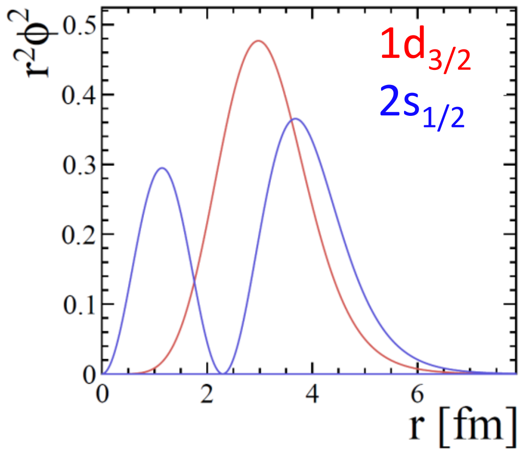
The sequence of L=2, L=0 and L=2 removal from the $d_{3/2}$, $s_{1/2}$ and $d_{5/2}$ orbitals is found with expected occupancy values

ΔM (^{36}Ca) = - 6480(40) keV agrees with penning trap measurement of ΔM (^{36}Ca) = - 6483.6(56) keV *Surbook et al. PRC 103 (2021)*

MED for the 2^+ and 1^+ states



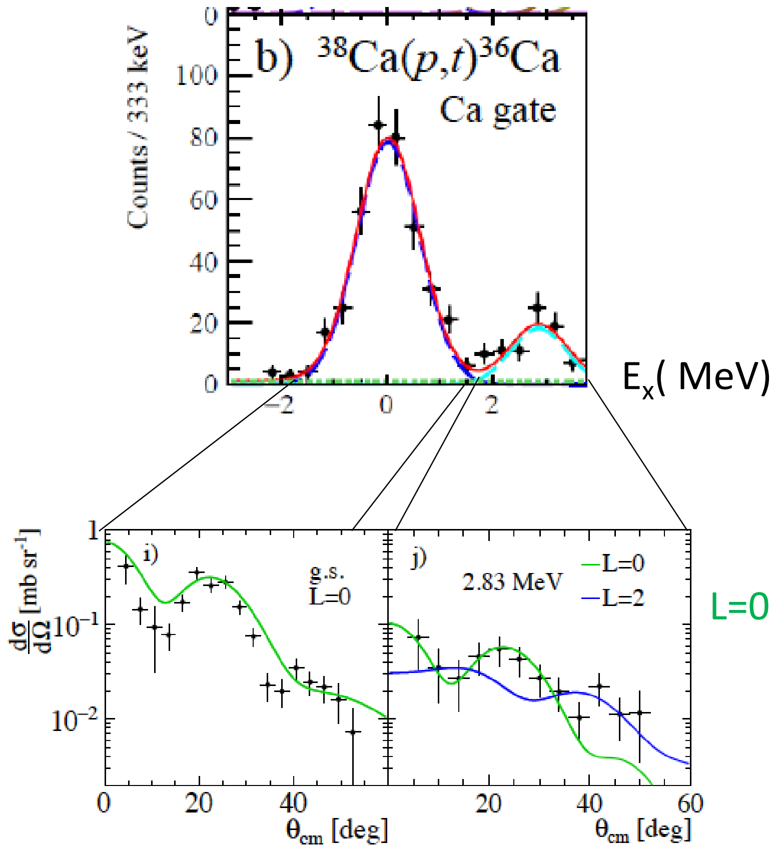




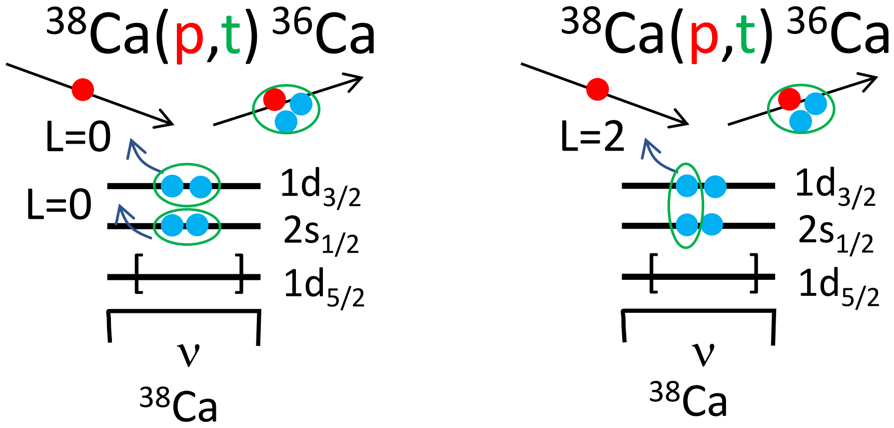
Compatible C^2S values between mirror nuclei

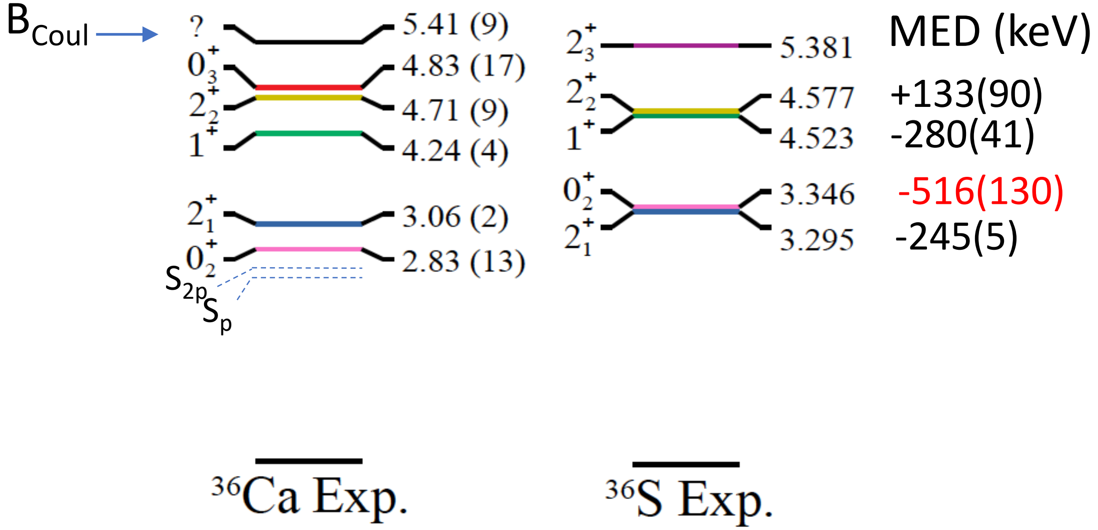
Upward shift of the (1,2)$^+$ states in ^{36}S as they feel more Coulomb repulsion than the g.s. does
The 0^+ ground state has 2 protons in the $2s_{1/2}$ orbital with rather large radius.
The (1,2)$^+$ state has a proton *(ph)* structure with one proton in $2s_{1/2}$ and the other in the $1d_{3/2}$ orbits (smaller r)

$^{38}Ca(p,t)^{36}Ca$ reaction to probe 0^+ states



L=0 pair transfer favoured

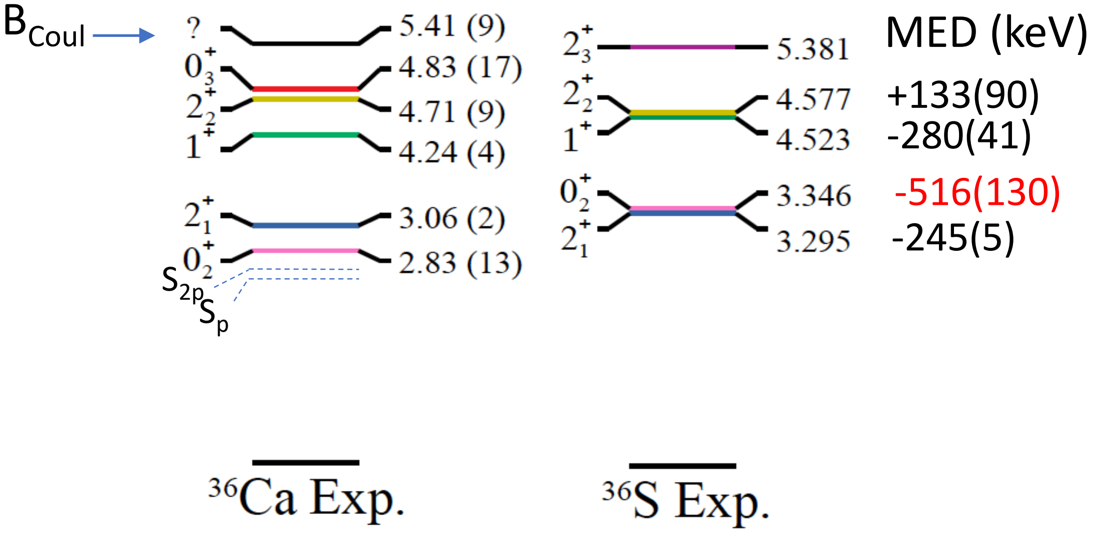


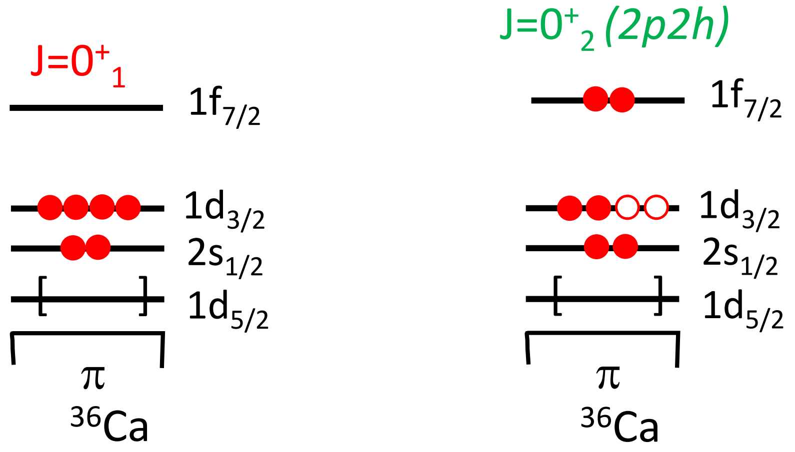


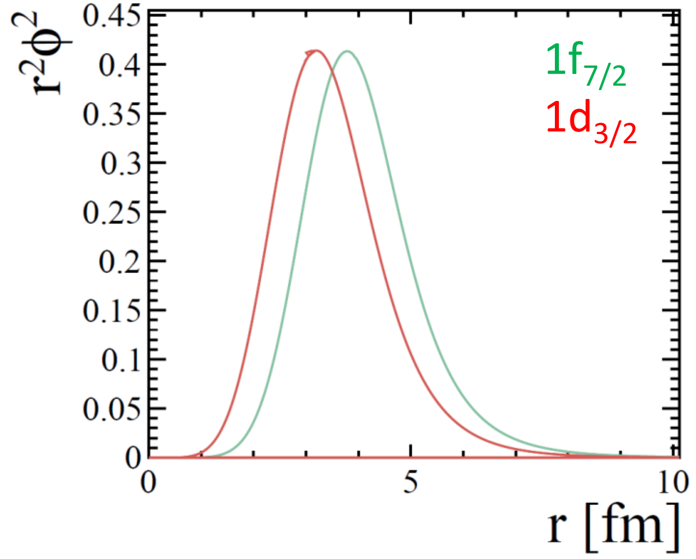
Very large MED between the 0^+_2 states -> first excited state in ^{36}Ca

L. Lalanne, O. Sorlin, A. Poves et al., to be submitted

MED for the 0^+_2







Very large MED between the 0^+_2 states -> first excited state in ^{36}Ca

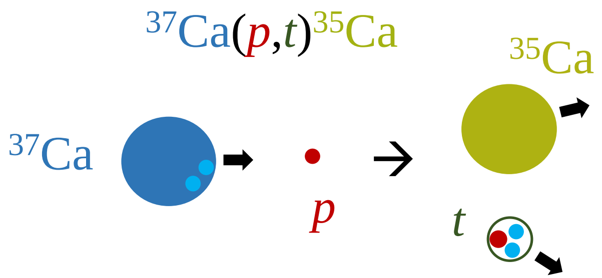
Closed-shell for 0^+_1 and deformed π(2p2h) & ν(1p1h) for 0^+_2 in ^{36}Ca

-250 (^{36}Ca) & +250 (^{36}S) = -500 keV

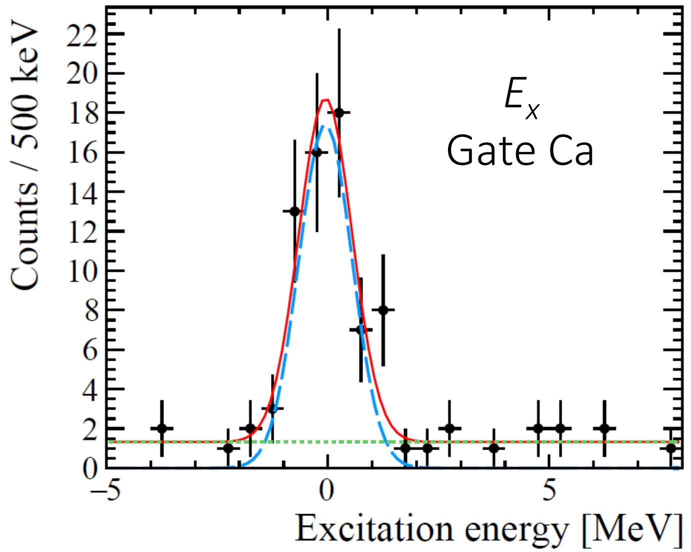
Colossal shift of the 0^+_2 state as cumulated effects

Coulomb force does not change the structure betweeen the mirror states but highlights their configuration

^{36}Ca: a new doubly-magic nucleus



Only one bound state in ^{35}Ca

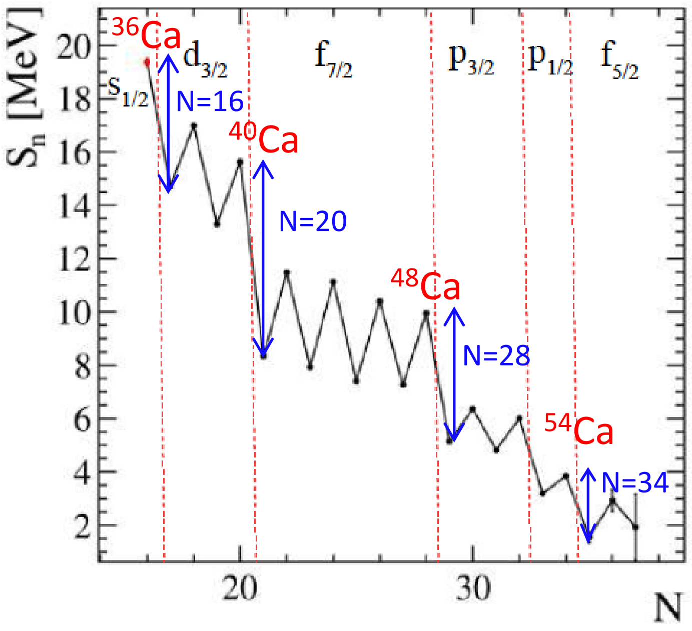


→ First mass measurement of ^{35}Ca

$$\Delta M(^{35}Ca) = (-4805 \pm 140)keV$$

-> $S_n(^{36}Ca)$ = 19.36(15) MeV

Gap(N=16) ≈ $S_n(^{37}Ca) - S_n(^{36}Ca)$



Gap (N=16) = 4.60(15) MeV

N=28 and N=16 gaps have comparable sizes
-> N=16 magic number

Gap (N=28) = 4.8 MeV

Gap(N=34) ≈ 2.28(18) MeV
'Evidence for a new magic number N=34, Magic nature of ^{54}Ca'
Steppenbeck Nature (2013), Michimasa PRL 121 (2018)

Conclusions

^{36}Ca proven to be a doubly-magic nucleus: N=16 gap = 4.60(15) MeV

Its ground and excited states exhibit rather pure configurations

Its Intruder state 0^+_2 has very different structure from the 0^+_1 ground state

Coulomb force induces significant changes between the binding energies of states in the mirror ^{36}Ca-^{36}S nuclei

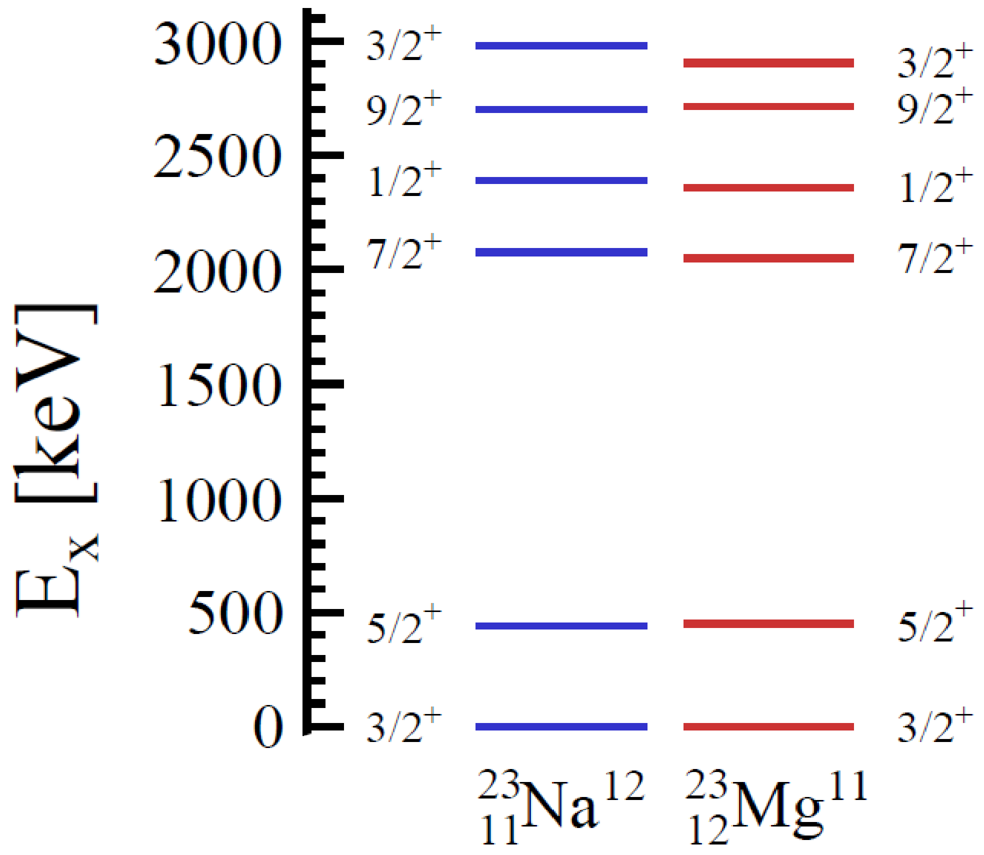
About -250 keV MED for the 2^+ and 1^+ states.

About -500 keV for the 0^+_2 the largest MED ever observed

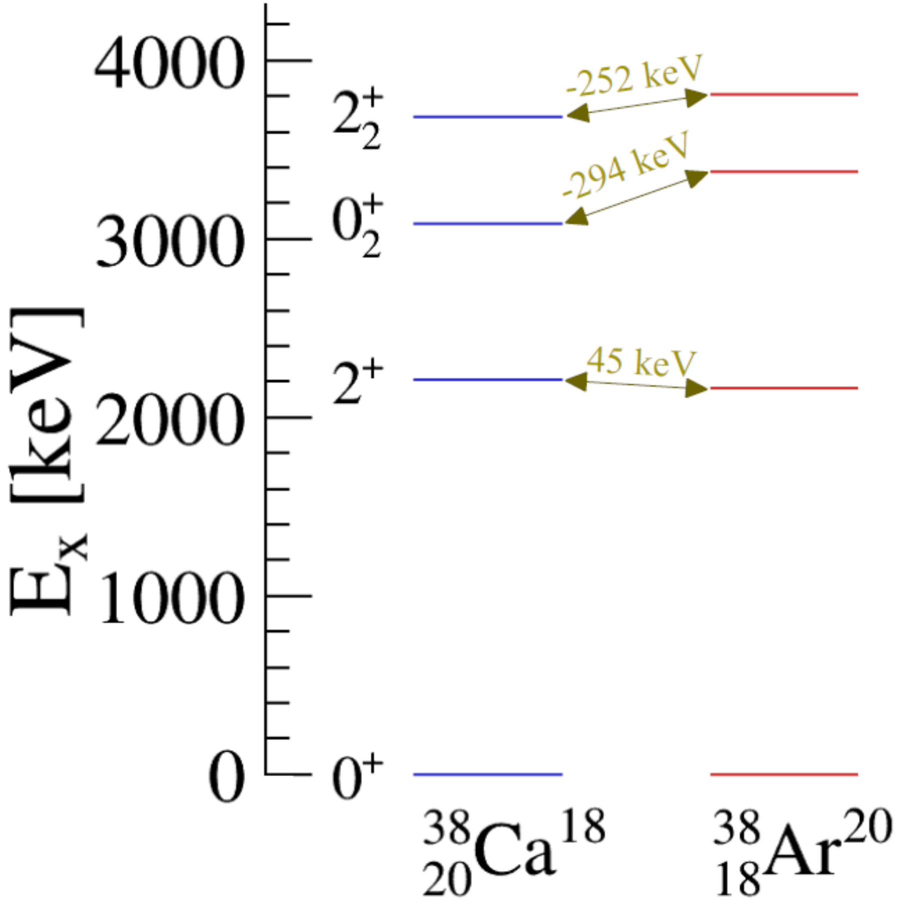
The breaking of MED is evidenced for the first time in the case of shape coexistence thanks to the double-magicity of ^{36}Ca

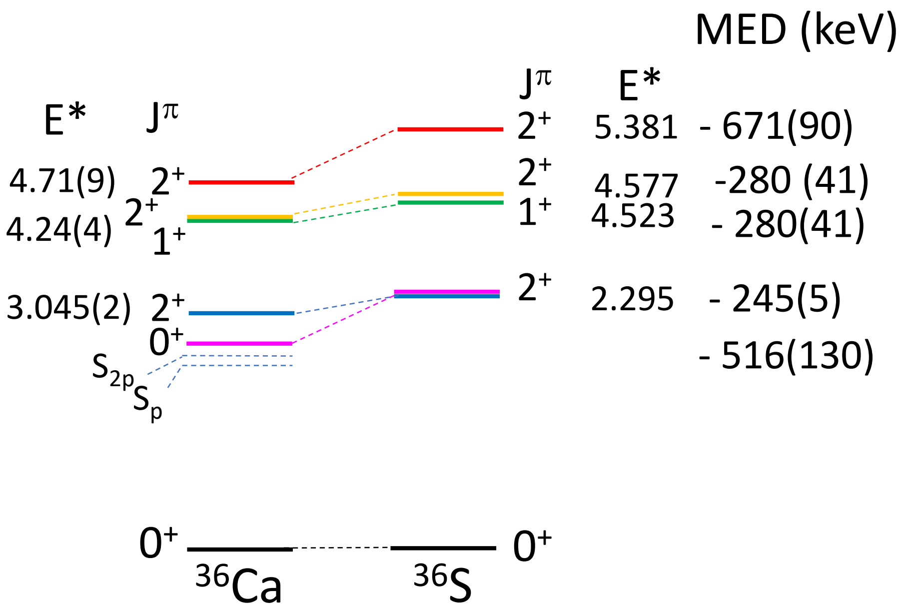
Backup slides

Small MED < 100 keV

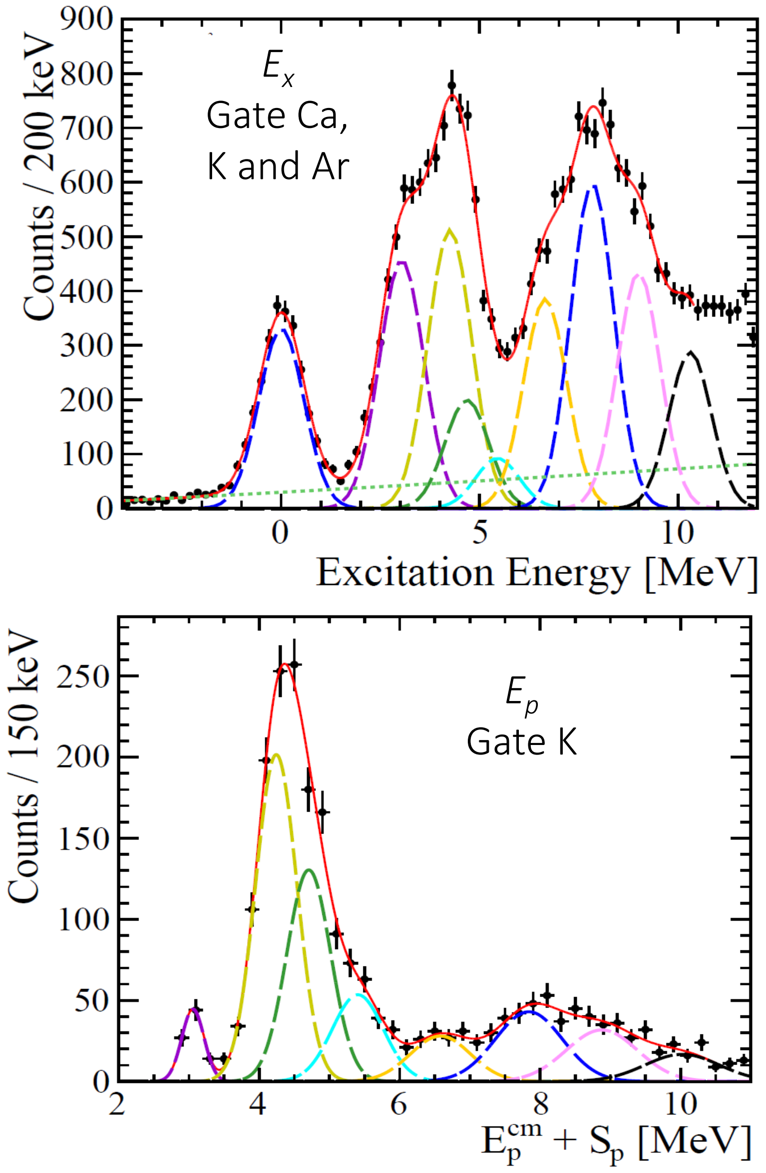


Large MED > 250 keV

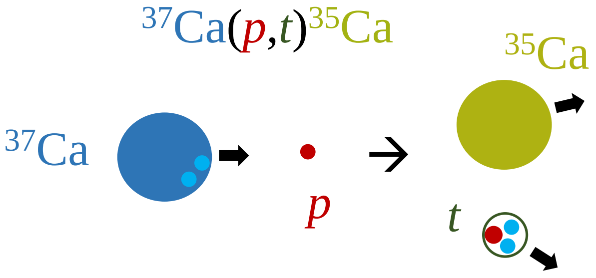


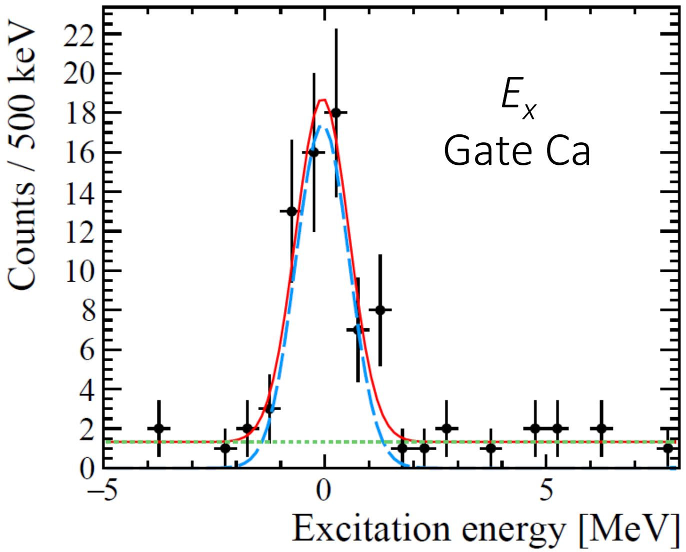


MED (keV)
E*
Jπ
Jπ
E*
4.71(9)
2+
2+
5.381
- 671(90)
2+
4.577
-280 (41)
4.24(4)
2+
1+
1+
4.523
- 280(41)
3.045(2)
2+
2+
2.295
- 245(5)
0+
- 516(130)
S2p
Sp
0+
0+
36Ca
36S



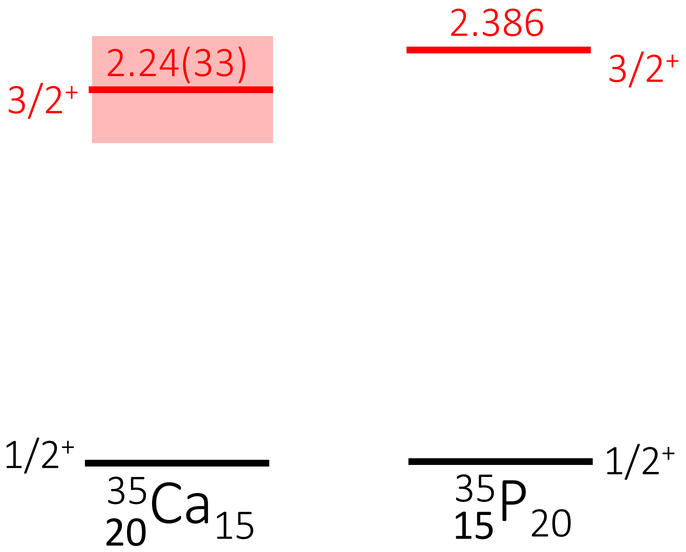
E_x
Gate Ca,
K and Ar
Counts / 200 keV
Excitation Energy [MeV]
0
100
200
300
400
500
600
700
800
900
0
5
10
E_p
Gate K
Counts / 150 keV
$E_p^{cm} + S_p$ [MeV]
0
50
100
150
200
250
2
4
6
8
10

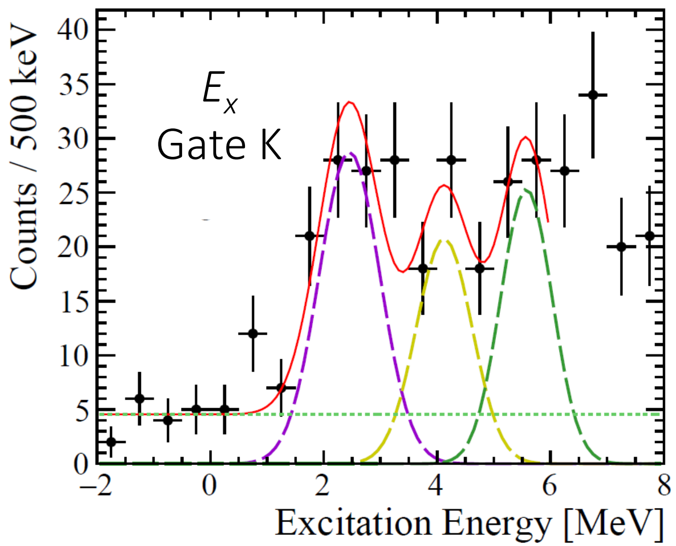




→ First mass measurement of ^{35}Ca

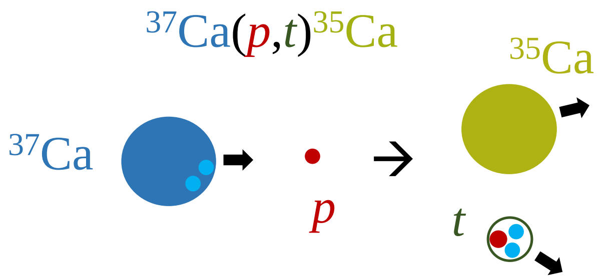
$$\Delta M = (-4805 \pm 140) keV$$

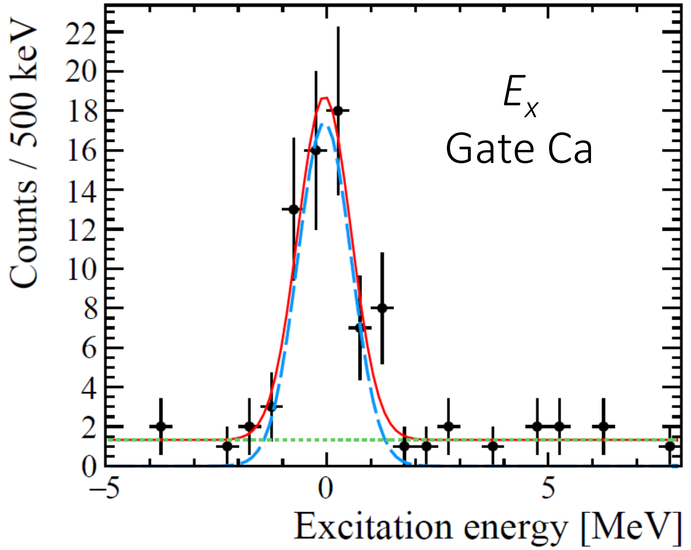




→ Discovery of the first $3/2^+$ excited state of ^{35}Ca

^{36}Ca: a new doubly-magic nucleus





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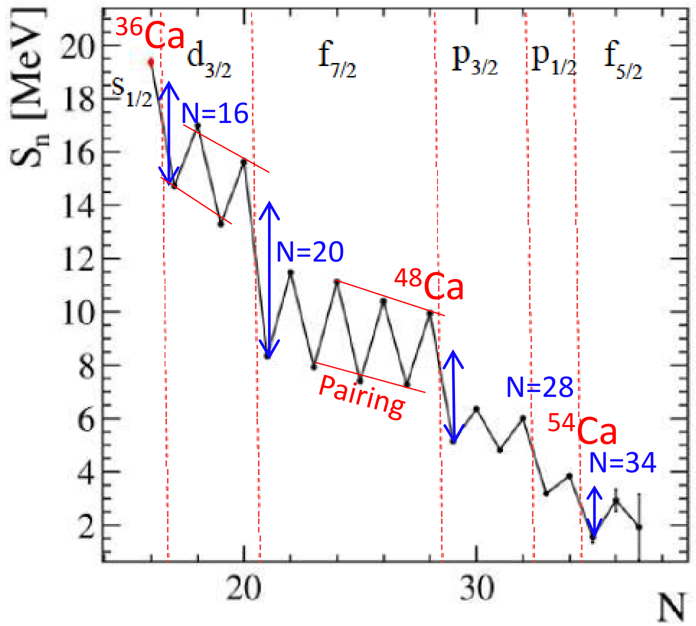


Other arguments in favor of magicity:

Centoid of *ph* excitation states at 3.8 MeV

C^2S close to ‘single-particle’ values

Gap (N=16) ≈ 3.5 MeV

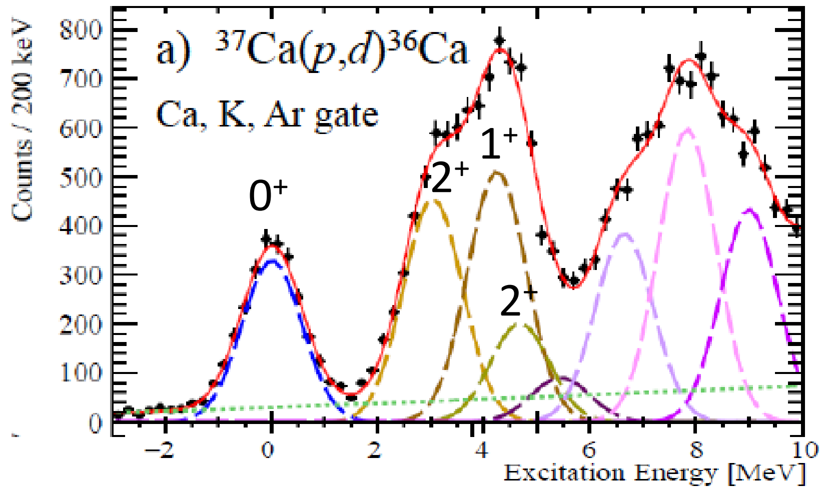
Gap (N=20) ≈ 5.5 MeV

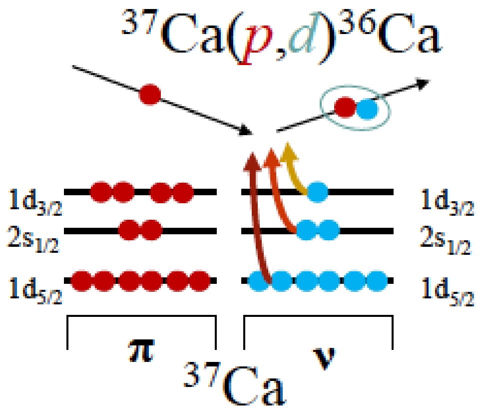
Gap (N=28) ≈ 3.5 MeV

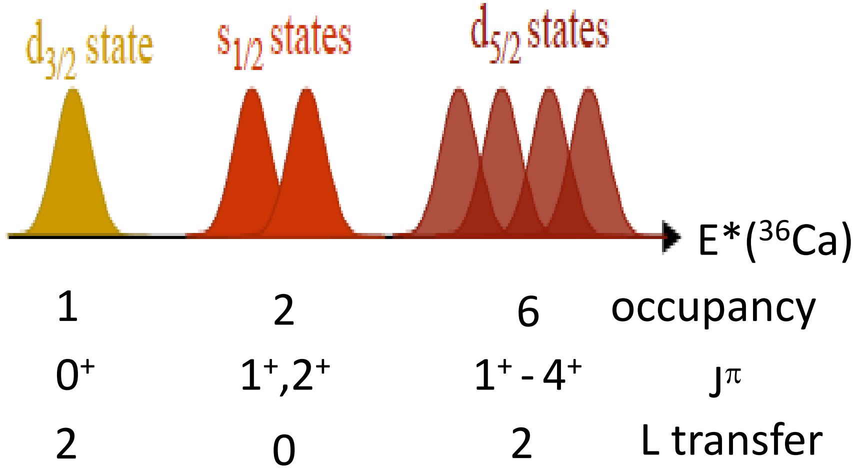
N=28 and N=16 gaps have comparable sizes -> N=16 magic number

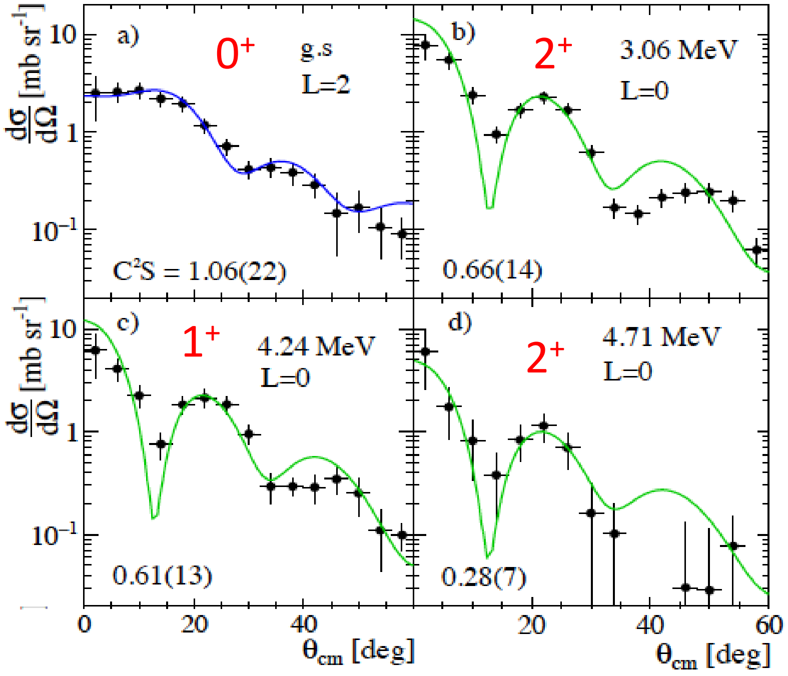
Gap(N=34) ≈ 2 MeV
‘Evidence for a new magic number N=34’
Steppenbeck et al., Nature (2013)

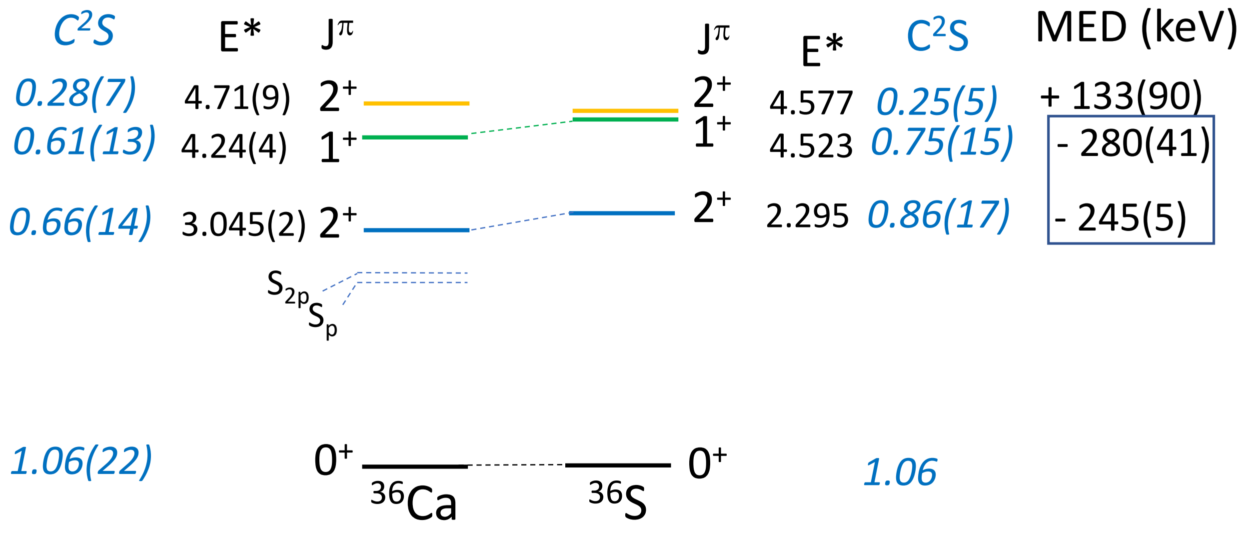
^{37}Ca(p,d)^{36}Ca reaction to probe neutron-hole states











(1,2)$^+$ states in ^{36}S have more repulsive Coulomb force than the g.s. due to their proton *(ph)* structure from $2s_{1/2}$ (large r) to $1d_{3/2}$ orbits (smaller r)