Isospin Symmetry along the $N = Z$ Line in sd Shell

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- Why Mirror Nuclei
- Results for *fp* Shell
- Extension to other Shells
- Our Experiment: A=31, 35
- Spin-orbit term and isospin mixing
- Conclusion

Why Mirror Nuclei

Charge independence of the strong interaction is one of the fundamental assumptions in Nuclear Physics.

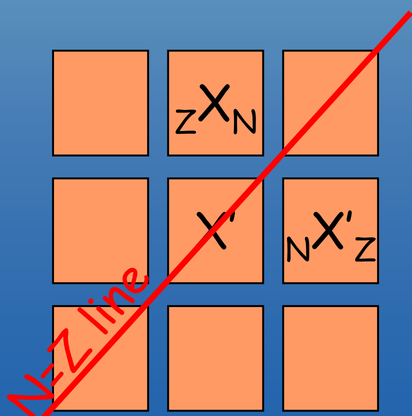
π ⟷ "nucleon" ⟷ $T_z=+1/2$

ν — Isospin quantum number (T=1/2) — $T_z=-1/2$

Coulomb Interaction breaks Isospin Symmetry

…but is not enough to explain the experimental data!

Mirror Nuclei



Shifts between the excitation energy of a mirror pair

$$MED_J = E_J\,(Z>N) - E_J\,(Z<N)$$

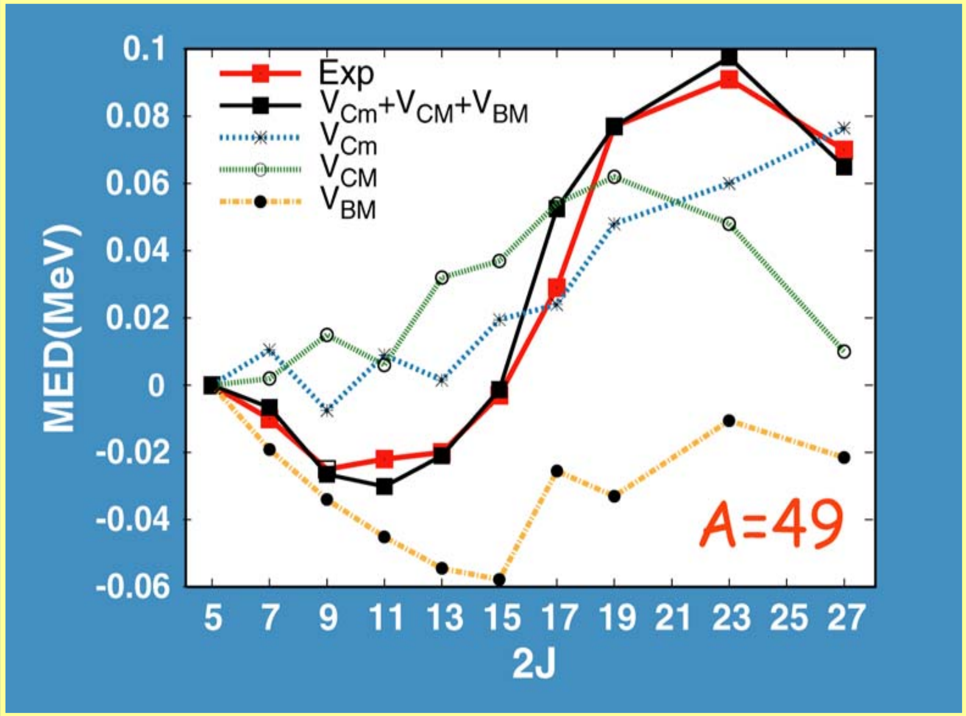
Results for fp Shell

✓A lot of experimental data
✓High quality wave functions

A part of nucleon-nucleon interaction
(isospin non conserving nuclear interaction)
is as important as the Coulomb potential!

$$\mathrm{MED}_J = \Delta_M \langle V_{CM} \rangle_J + \Delta_M \langle V_{Cm} \rangle_J + \Delta_M \langle V_B \rangle_J$$

Coulomb (first two terms) — **isospin breaking nuclear** (last term)



A.P. Zuker *et al.*, PRL 89 (2002) 142502
M.A. Bentley *et al.*, PLB 437 (1998) 243

Extension to other Shells

We can apply our experience in the $f_{7/2}$ shell to other mass regions

- ✓ To check the limit of validity of the isospin symmetry for different masses
- ✓ To identify the origins of the symmetry breaking
- ✓ To look for the INC terms of the nuclear interaction
- ✓ To look for new Coulomb effects

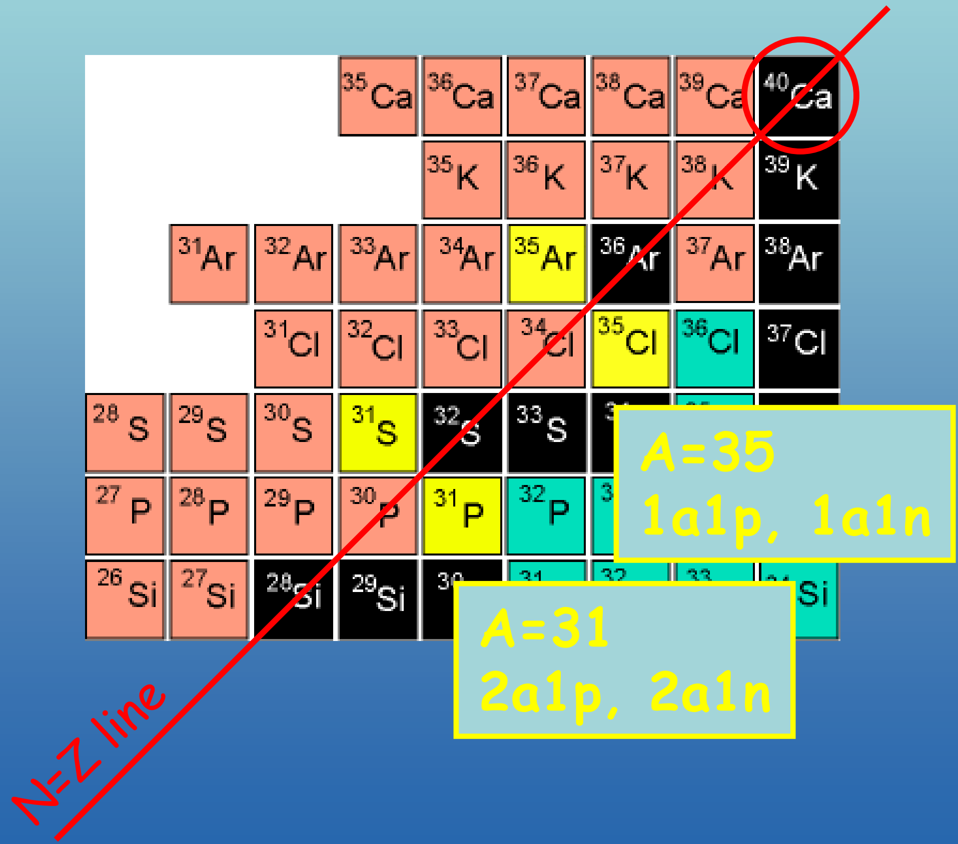
For a quantitative understanding we need:

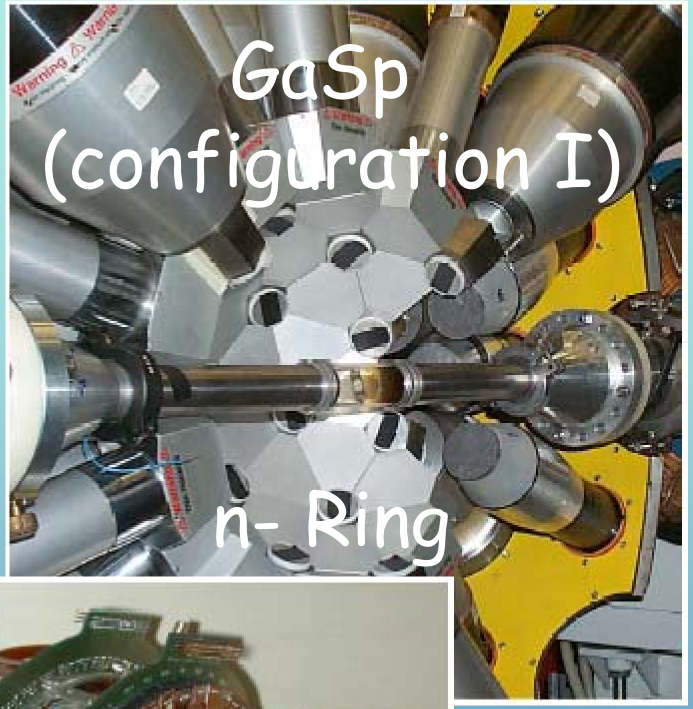
1) **to perform precise measurements of the different observables**
2) **to perform shell-model calculations on a large basis (more than one major shell) and with reliable effective interactions**

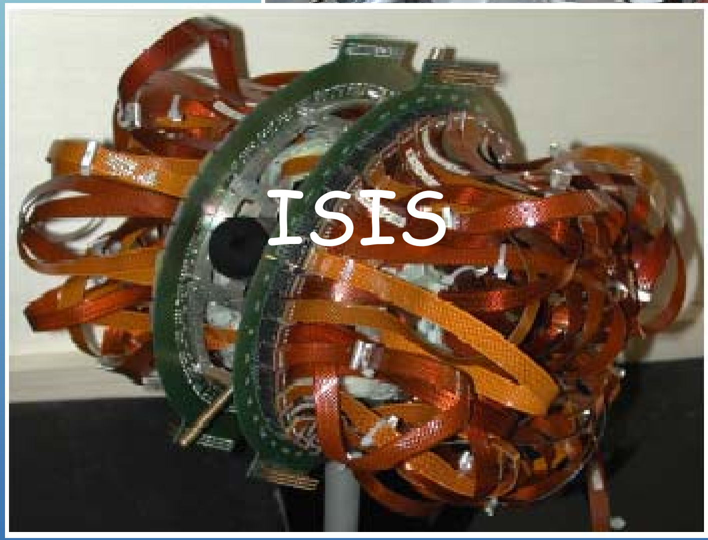
Experiment

The reaction

^{16}O (70 MeV) + ^{24}Mg (400 μg/cm²)







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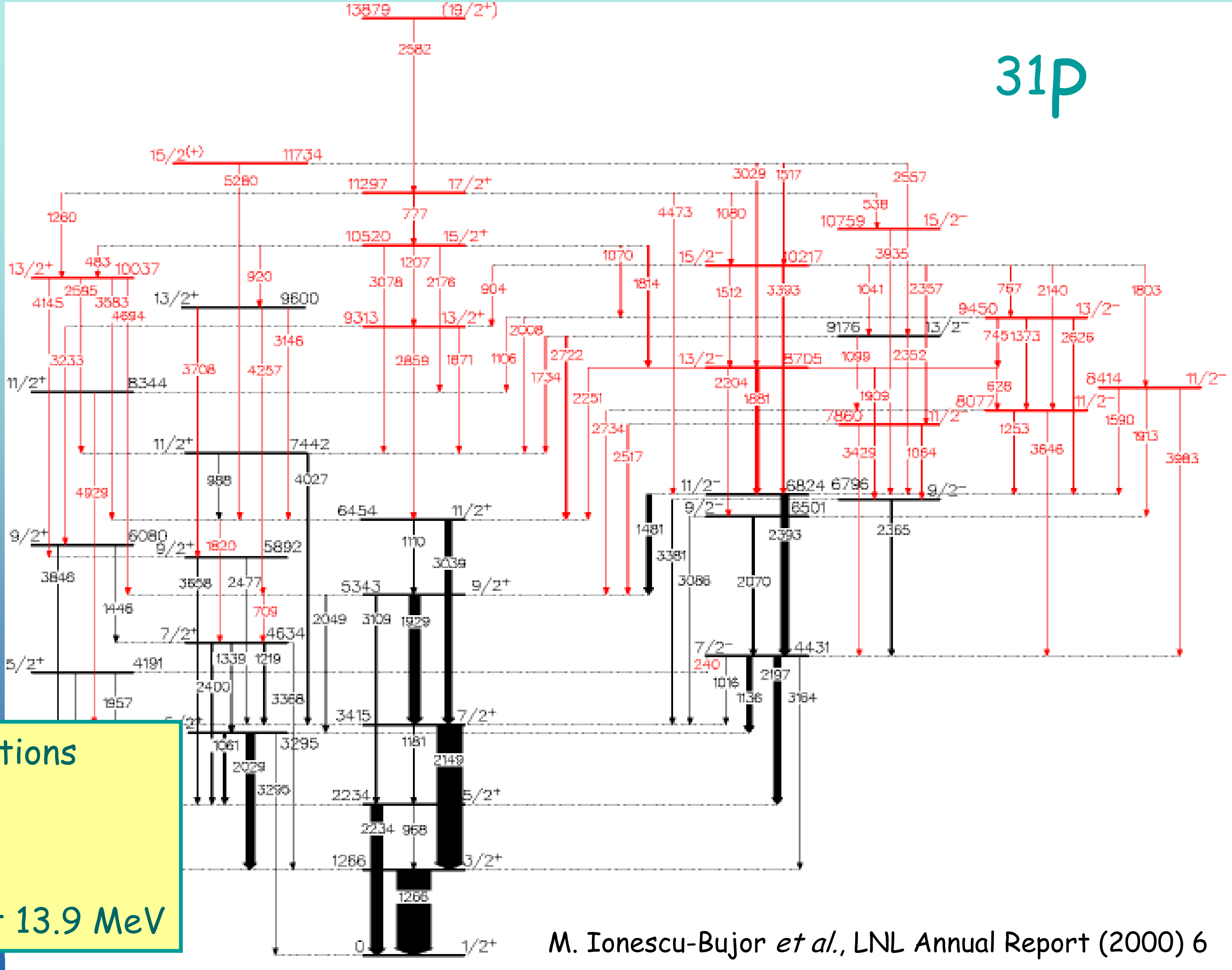
A=31

2α1p channel



50 new transitions

14 new levels

up to $19/2^+$ at 13.9 MeV

M. Ionescu-Bujor *et al.*, LNL Annual Report (2000) 6

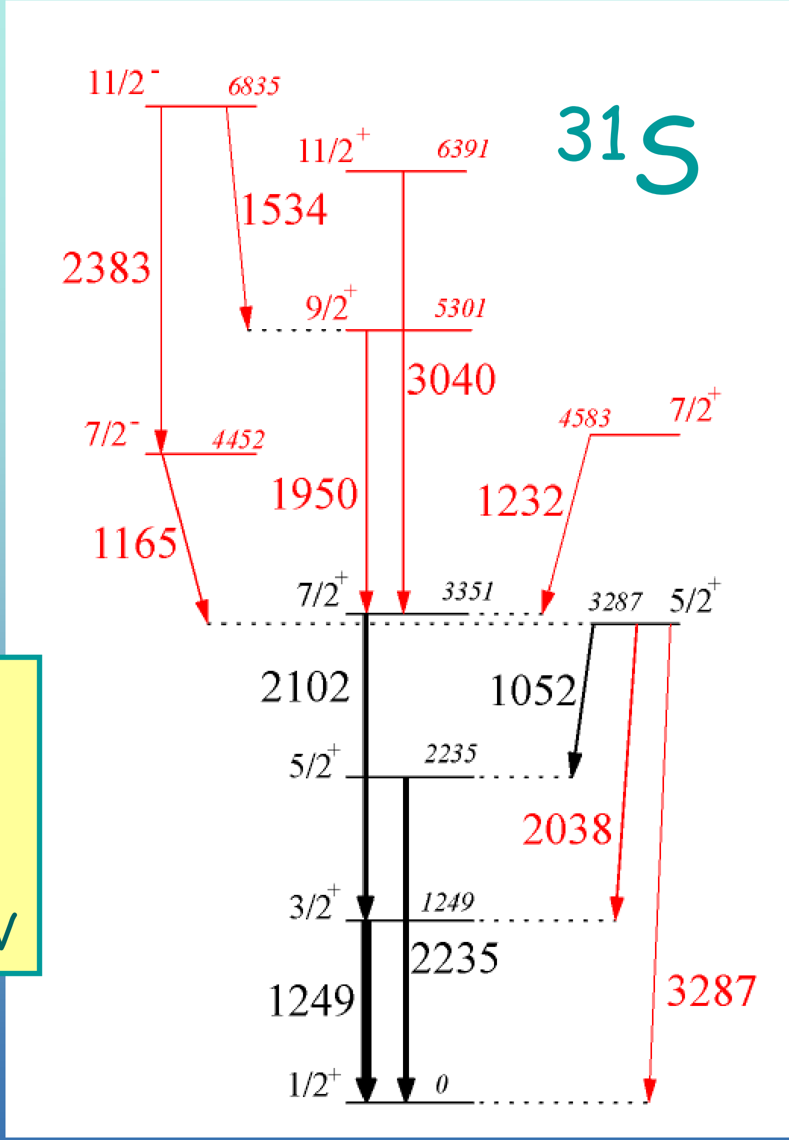
A=31

2a1n channel

8 new transitions

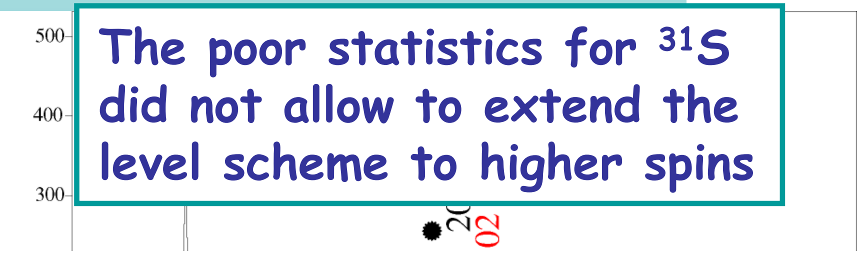
5 new levels

up to 11/2$^-$ at 6.8 MeV

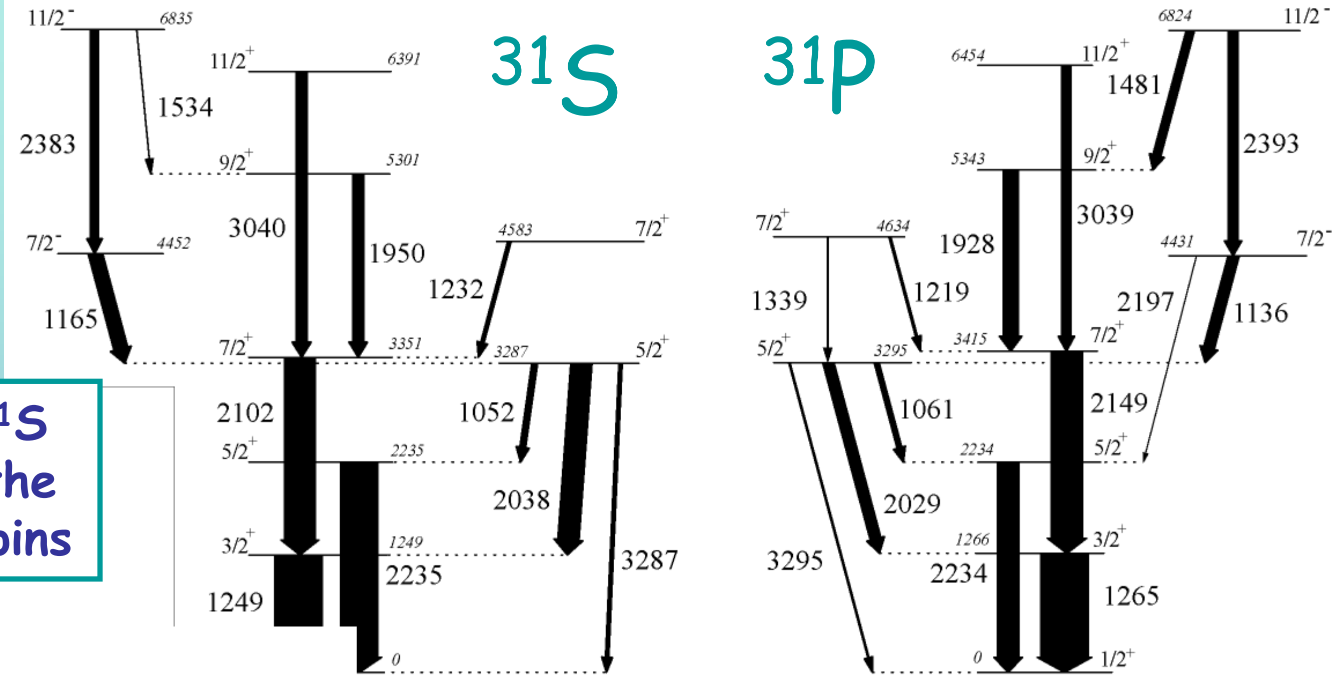


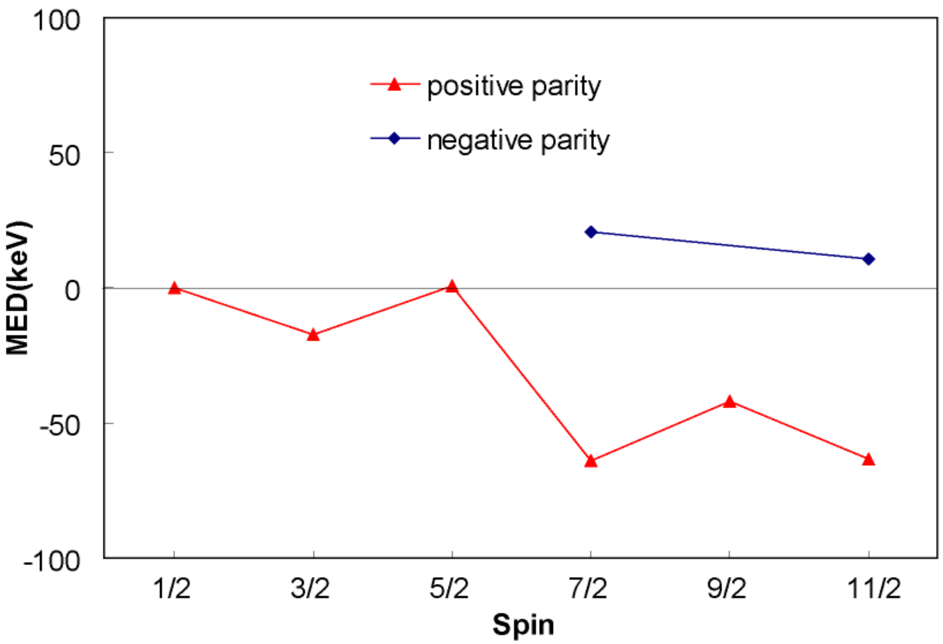
F. Della Vedova *et al.*, LNL Annual Report (2003) 3

MED A=31



The poor statistics for ^{31}S did not allow to extend the level scheme to higher spins



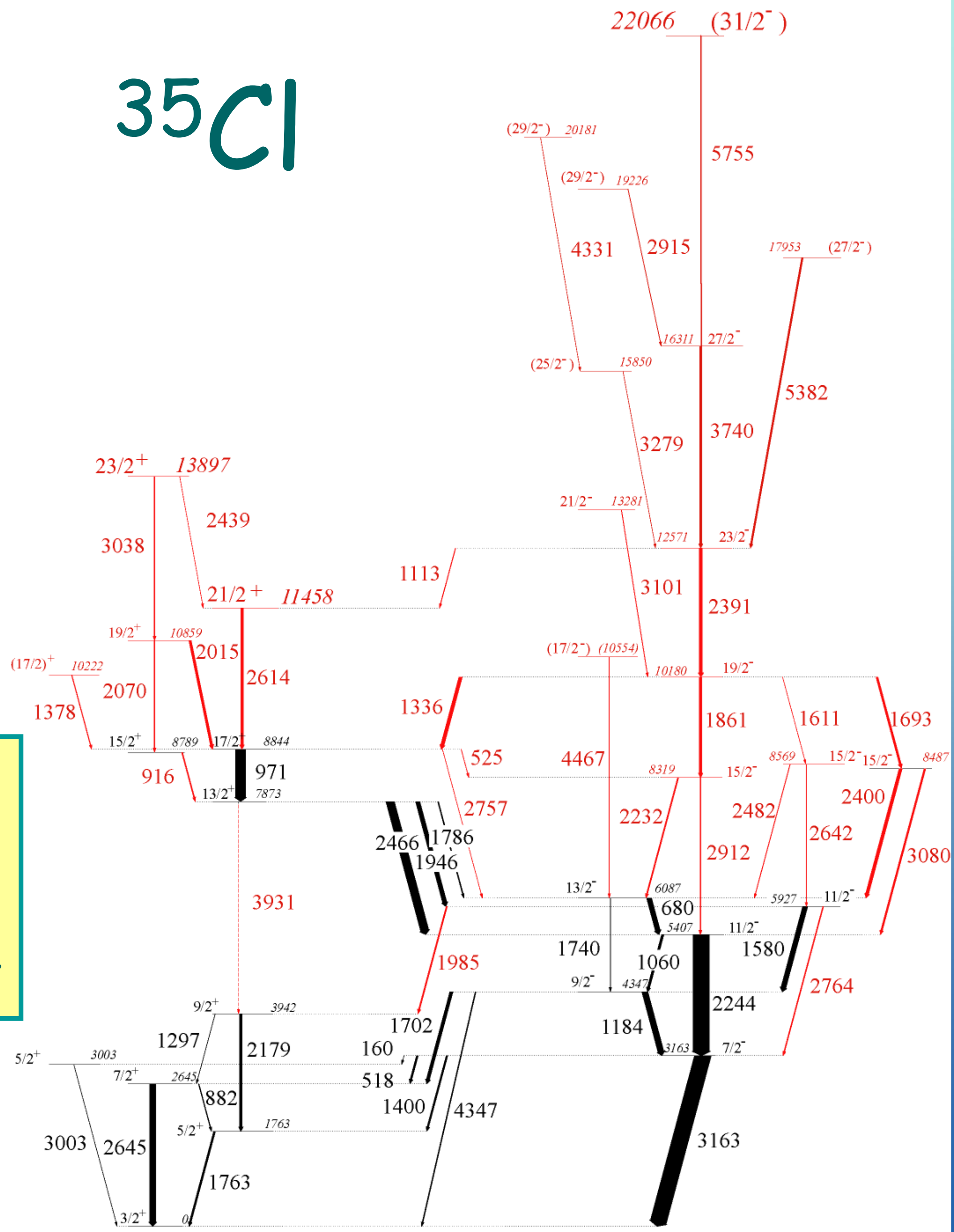


- ✓MED of the same order of that in $1f_{7/2}$
- ✓Staggering effect
- ✓Theoretical calculations are not enough precise to reproduced this behaviour

New experiment in program

A=35

1a1p channel



32 new transitions

17 new levels

up to 31/2⁻ at 22 MeV

Shell Model Calculations

Ingredients:

- Valence space
- Interaction

→ High spin structure and negative parity

- Larger valence space (excitations involving fp shell)
- Cross-shell interactions

→ Low spin structure

- sd shell
- USD (Wildenthal-Brown) Ann. Rev. Nucl. Part. Sci. **38** (1988) 29

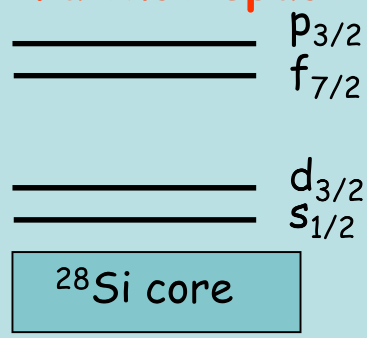
The interactions used for neutron rich nuclei (protons in the sd and neutrons in the fp shell) do not work very well near N=Z line

Recent calculations for ^{34}S

P. Mason *et al.*, to be published

In this region these SM calculations
✓give good wave functions
✓reproduce the decay pattern
…but need to be improved!

Valence space



sdpf interaction

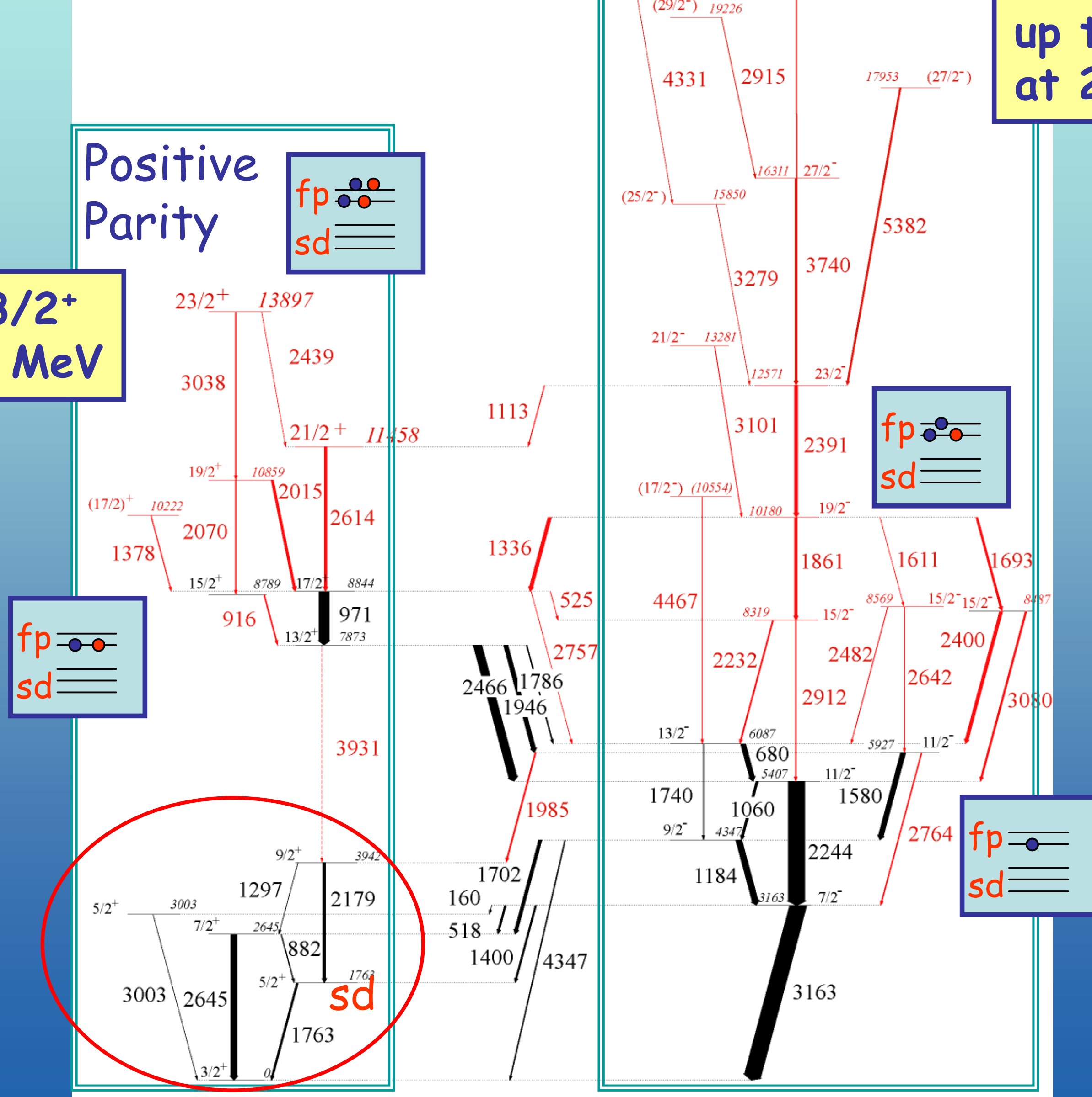
- USD interaction for sd shell
- KB3 interaction for fp shell
- cross shell interaction of Kahanna, Lee and Scott

A=35

1a1p channel

up to $23/2^+$ at 13.9 MeV

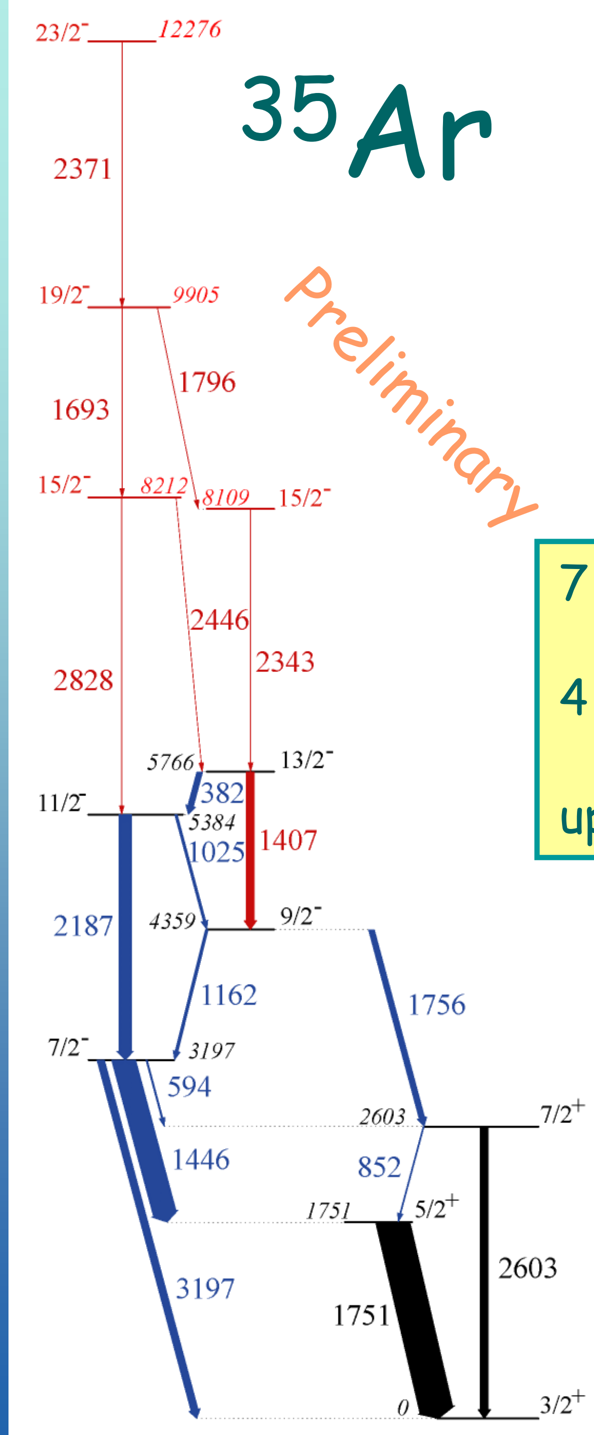
^{35}Cl



up to $31/2^-$ at 22 MeV

A=35

1a1n channel



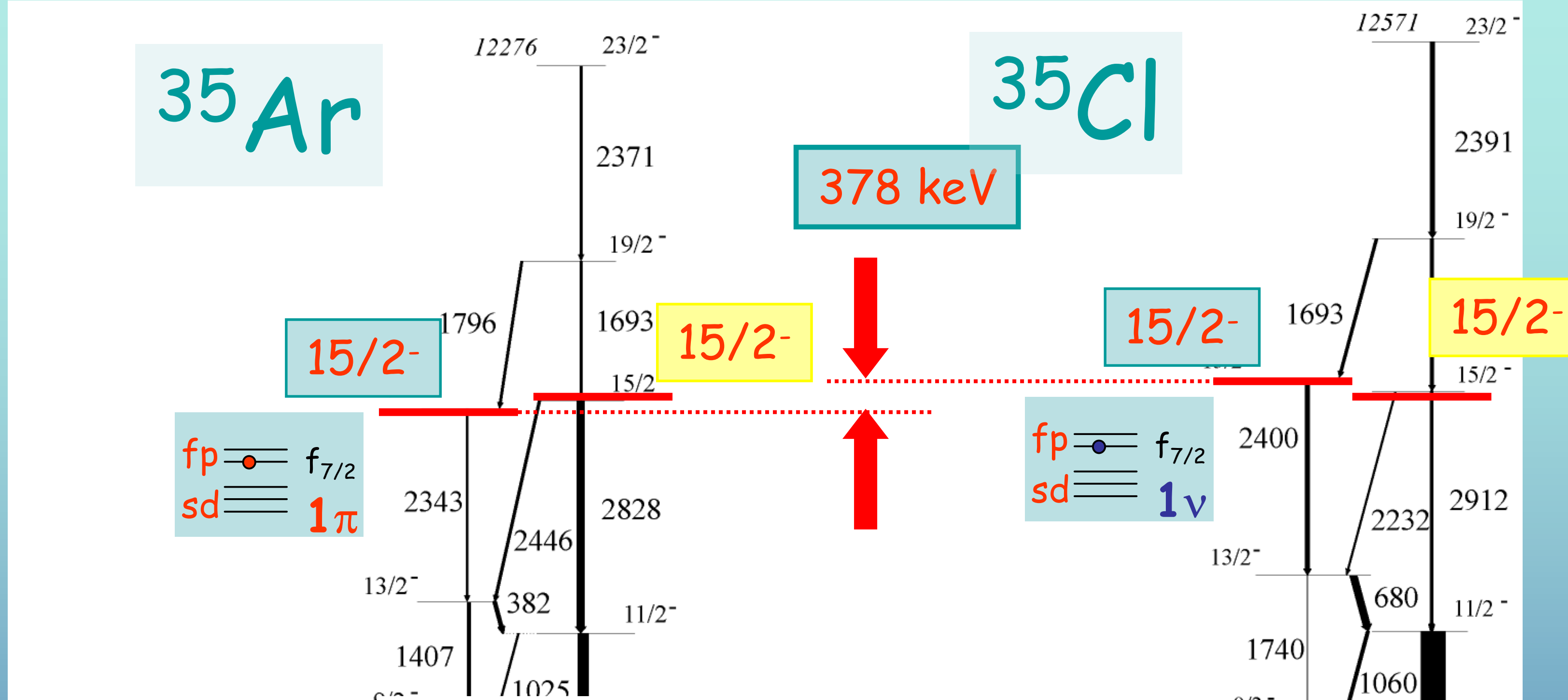
7 new transitions

4 new levels

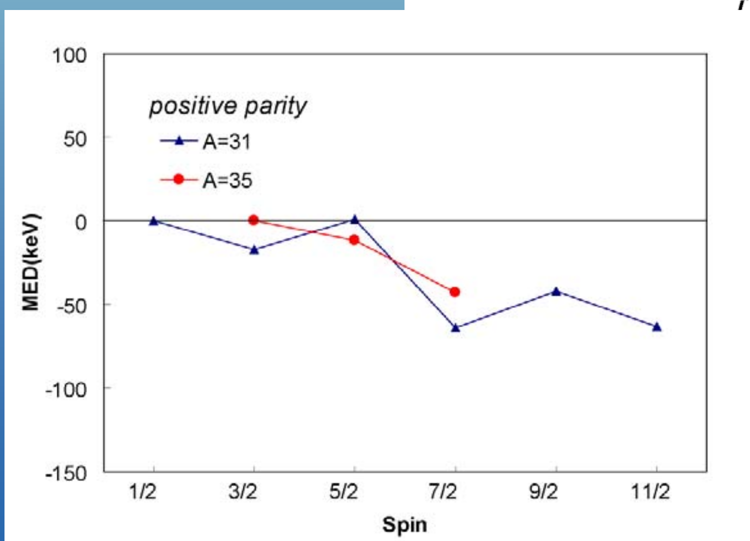
up to 23/2⁻ at 12.3 MeV

Previous work (blue transitions)
J. Ekman *et al.*, PRL 92 (2004) 132502

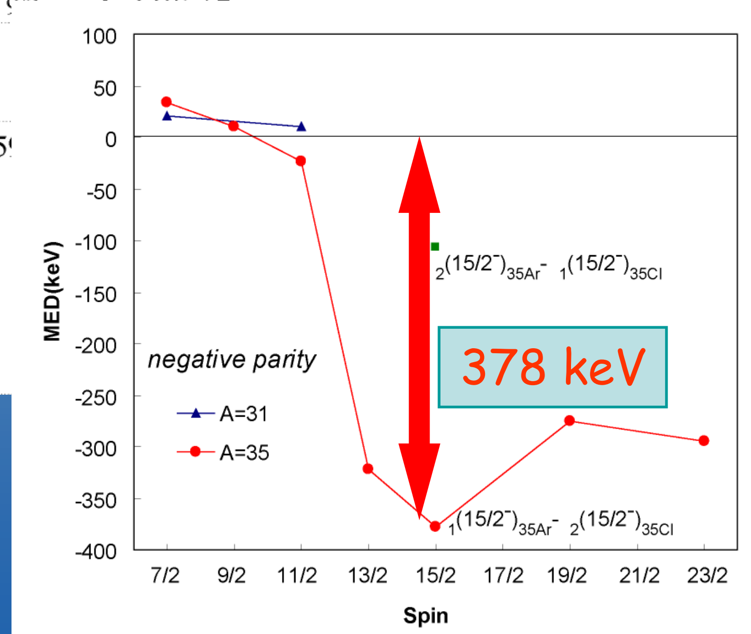
MED



^{35}Ar
^{35}Cl
378 keV
15/2-
15/2-
15/2-
15/2-
fp $f_{7/2}$
sd 1π
fp $f_{7/2}$
sd 1ν
12276 23/2-
2371
19/2-
1796
1693
15/2
2343
2446
2828
13/2-
382
11/2-
1407
1025
12571 23/2-
2391
19/2-
1693
15/2-
2400
2232
2912
13/2-
680
11/2-
1740
1060
9/2-
2244
1702
1184
7/2-
518
1400
3163



positive parity
A=31
A=35
MED(keV)
Spin
100
50
0
-50
-100
-150
1/2
3/2
5/2
7/2
9/2
11/2



negative parity
A=31
A=35
MED(keV)
Spin
378 keV
$_2(15/2^-)_{35Ar} - _1(15/2^-)_{35Cl}$
$_1(15/2^-)_{35Ar} - _2(15/2^-)_{35Cl}$
100
50
0
-50
-100
-150
-200
-250
-300
-350
-400
7/2
9/2
11/2
13/2
15/2
17/2
19/2
21/2
23/2

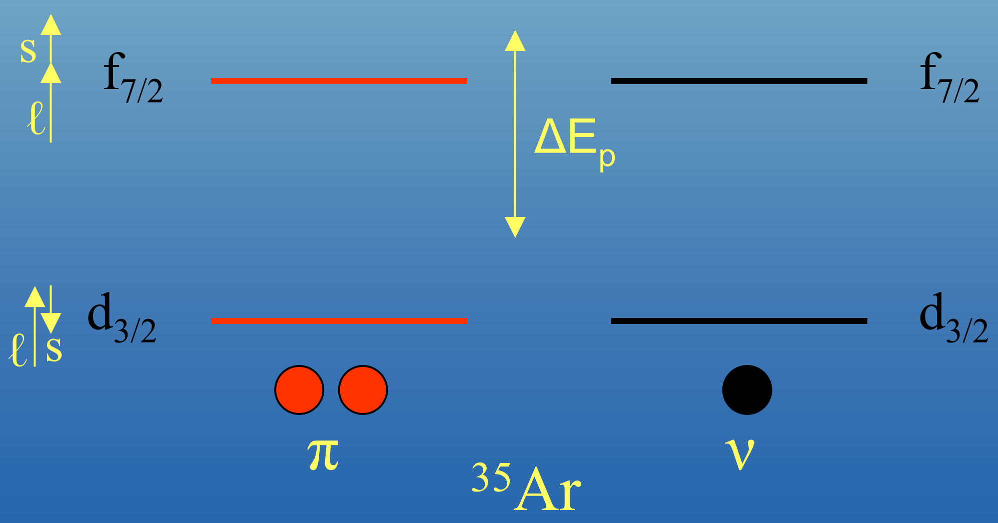
The spin-orbit term

$$\mathrm{MED}_J = \Delta_M \langle V_{CM} \rangle_J + \Delta_M \langle V_{Cm} \rangle_J + \Delta_M \langle V_B \rangle_J$$

Coulomb monopole term contains a **spin-orbit term**

The electromagnetic spin-orbit coupling results from the Larmor precession of the nucleons in the nuclear electric field due to their intrinsic magnetic moments and to the Thomas precession experienced by a proton because of its charge.

$$V_{ls} = (g_s - g_l)\frac{1}{2m_N^2 c^2}\left(\frac{1}{r}\frac{dV_C}{dr}\right)\mathbf{l.s}$$



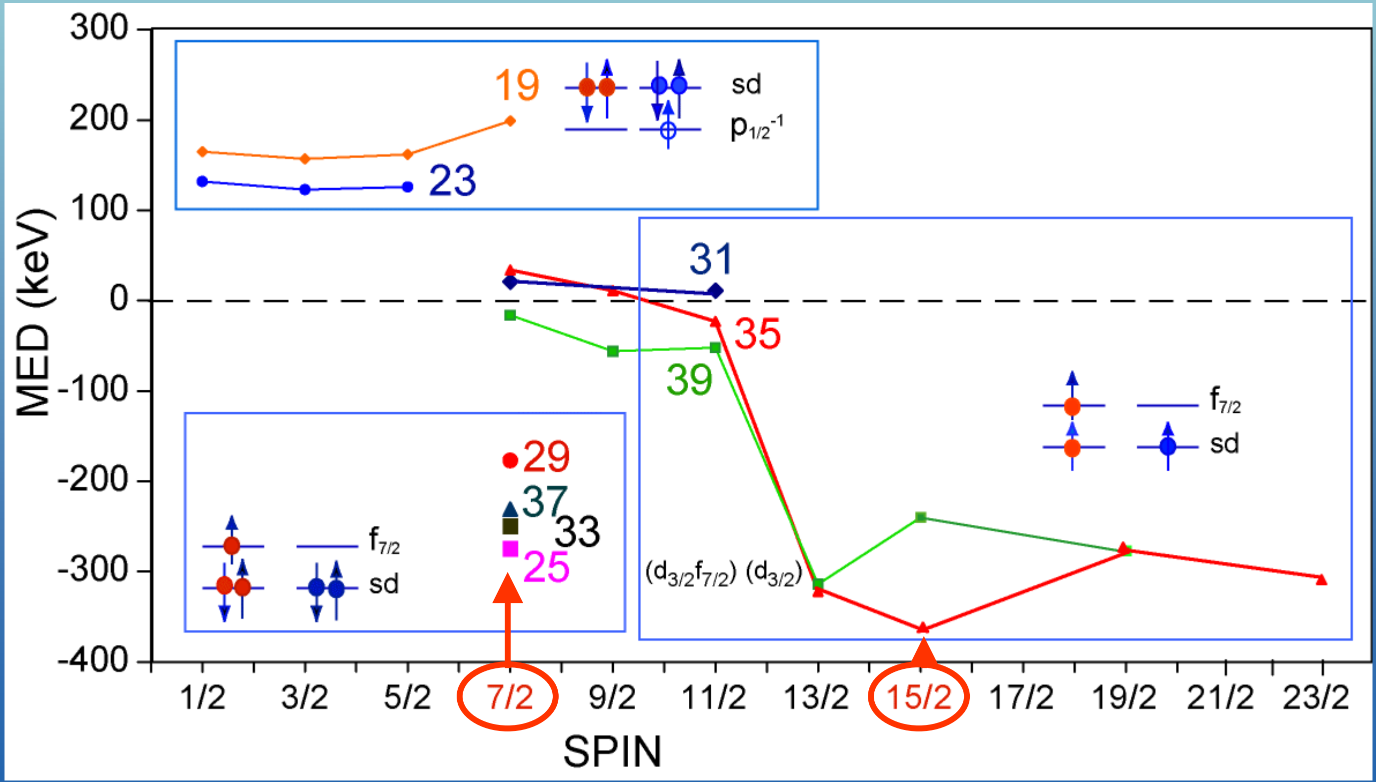
It is important when a nucleon is promoted from a j=l-s level to a j=l+s level.
The effect on a proton is opposite to the effect on a neutron orbit

J. Ekman *et al.*, PRL 92 (2004) 132502

The spin-orbit effect in the sd shell

The effect of the electromagnetic spin-orbit term is proportional to the difference of proton and neutron occupation numbers.

Its contribution to MED becomes significant for configurations with *pure* single-nucleon excitations: a proton excitation in one nucleus and a neutron excitation in its mirror



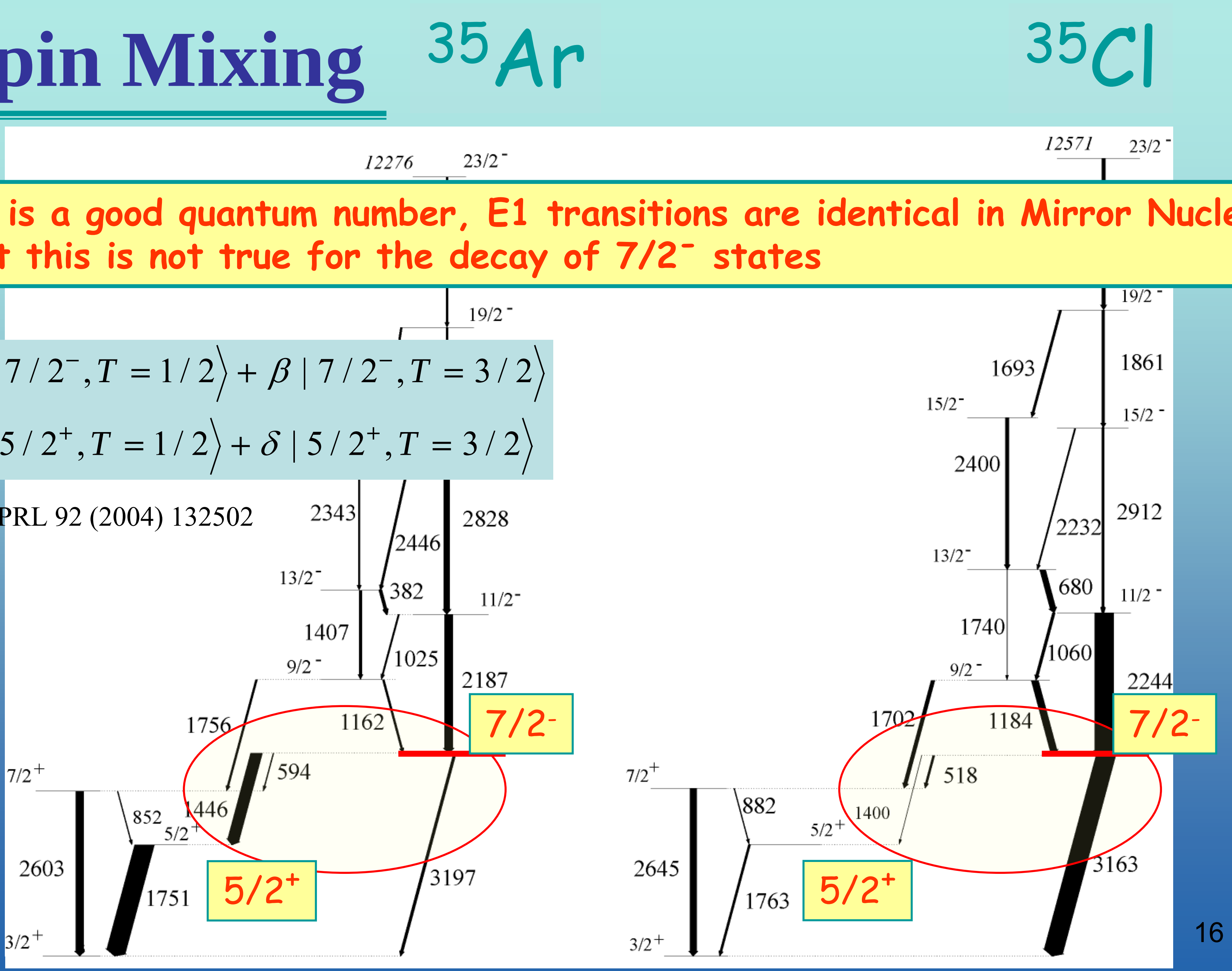
Isospin Mixing

If T is a good quantum number, E1 transitions are identical in Mirror Nuclei … but this is not true for the decay of 7/2⁻ states

$$|7/2^-\rangle = \alpha\,|7/2^-, T=1/2\rangle + \beta\,|7/2^-, T=3/2\rangle$$

$$|5/2^+\rangle = \gamma\,|5/2^+, T=1/2\rangle + \delta\,|5/2^+, T=3/2\rangle$$

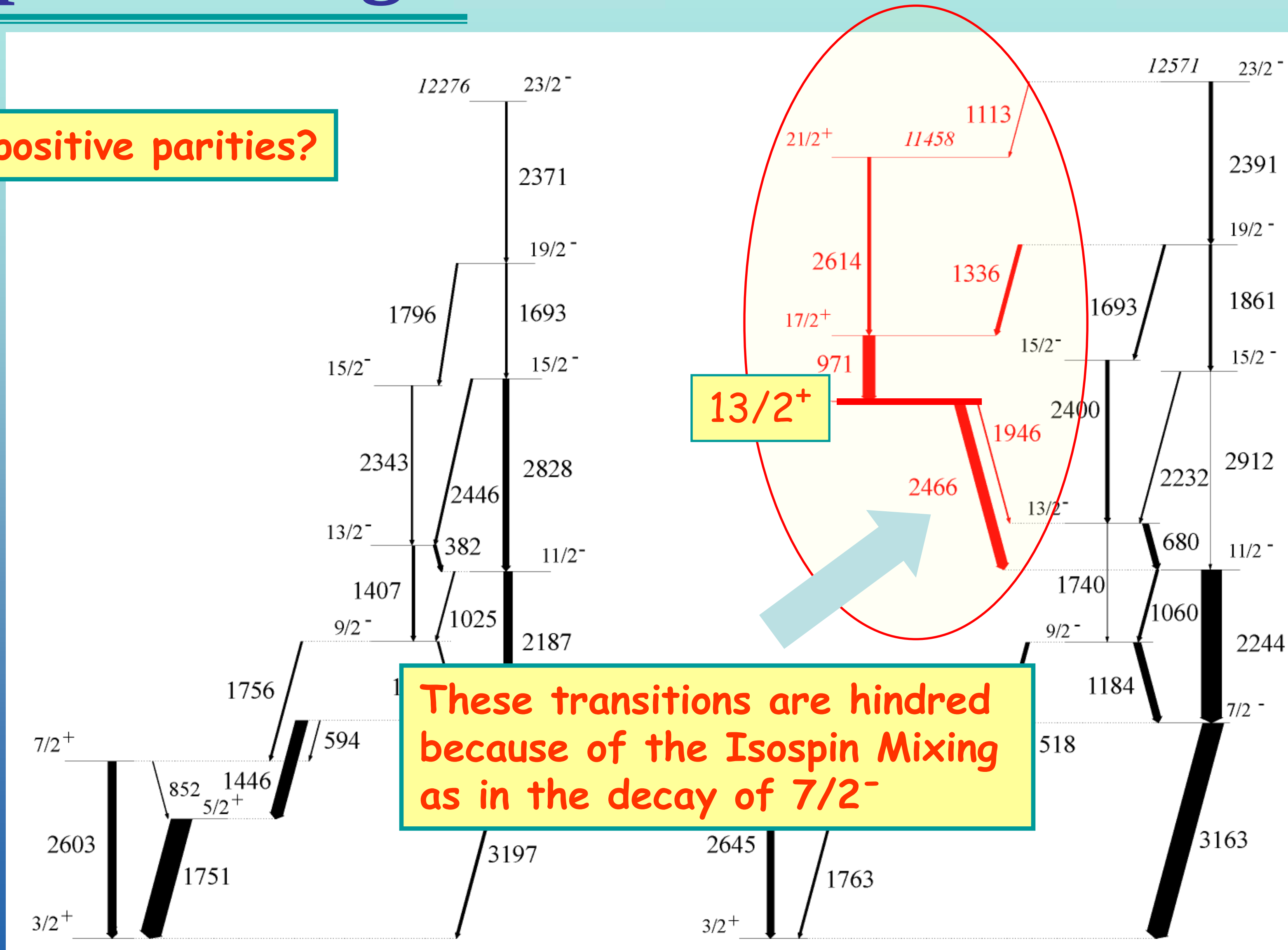
J. Ekman *et al.*, PRL 92 (2004) 132502



Isospin Mixing

^{35}Ar ^{35}Cl

High spin positive parities?



These transitions are hindred because of the Isospin Mixing as in the decay of 7/2⁻

Conclusions

The extension of study of Mirror Nuclei to sd shell has revealed **remarkable features:**

- ✓ Importance of the spin-orbit term which explains the systematics of the MED between negative parity states in all the sd-shell
- ✓ Direct evidence of isospin mixing through the E1 transitions

The understanding of these effects represents a challenging task

These investigations are at the beginning

We need

- ✓ Complete spectroscopy
- ✓ Better and reliable effective interactions, that take into account more than one shell

GASP Collaboration @ LNL

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