Spin-orbit splittings of neutron states in N = 20 isotones from covariant density functionals (CDF) and their extensions.

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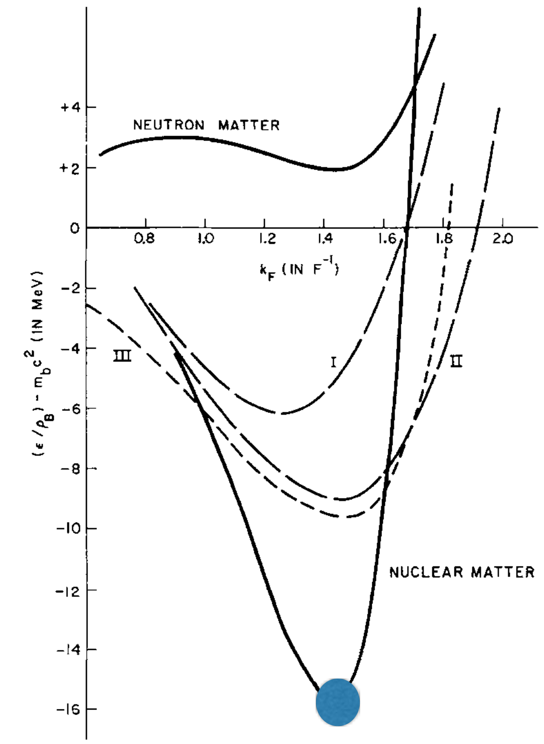
Motivation: history

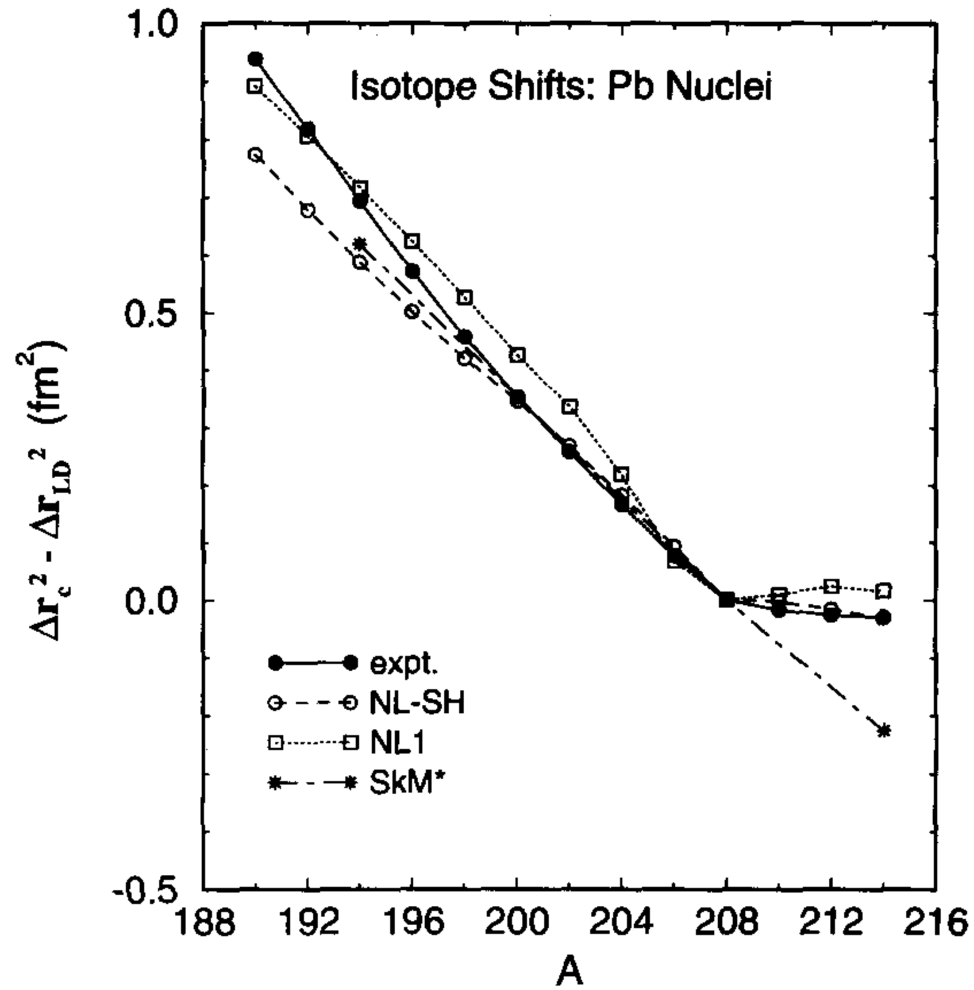
Main goal:
Examine isospin/density dependence of spin-orbit (SO) in CDFT

The spin orbit (SO) force introduced ~ 60 years ago corrects the shell gaps.



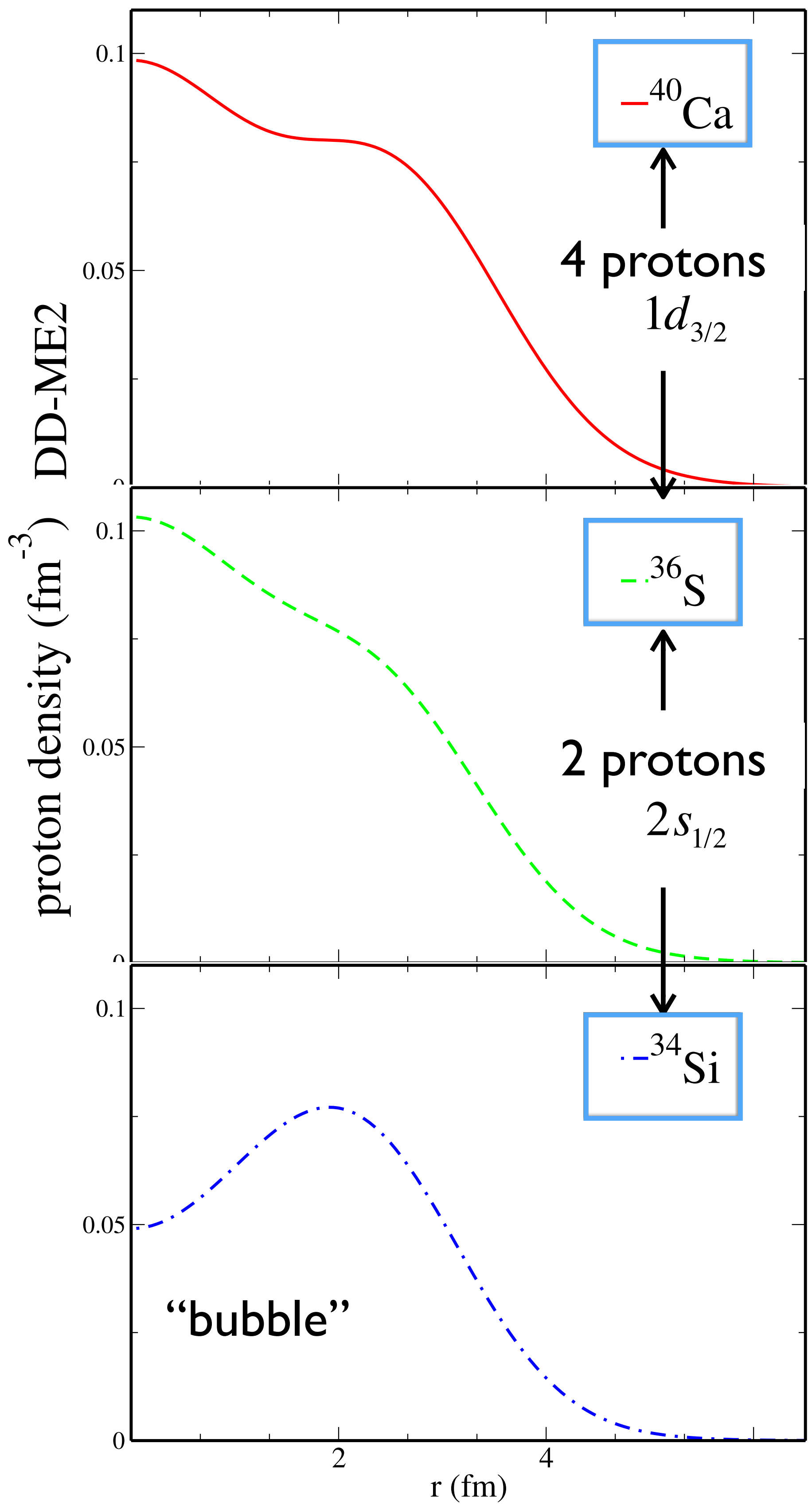
Non-Rel. MF
Skyrme: zero range
Gogny: finite range
Both use 2-body SO term - has to be adjusted

RMF
Based on the Walecka meson exchange model
Major advantage SO term naturally from Dirac eq.



Both approaches successful along stability line - similar results
SO difference appear in extreme isospin cases.
Well known example: isotopic shifts in charge radii in Pb

Motivation: the 34Si bubble experiment



<u>recent experiment effort - constraint on isospin dep. of SO</u>

Study $N = 20$ isotones 40Ca, 36S, 34Si

Concentrate on neutron states $2p = 2p_{1/2} - 2p_{3/2} \quad 1f = 1f_{5/2} - 1f_{7/2}$

<u>1st Adv.:</u> A ≈ 40 2*p* splitting around 2MeV and both SO partners accessible

<u>2n Adv.:</u> Occurrence of 'Bubble' in 34Si proton dens.

Theory: [M.Grasso *et.al.* , PRC 79,034318 (2009)]

Expt: [A.Mutschler, O. Sorlin *et.al.* NPHYS3916 (2016)]
knock-out reaction 34Si(-1p)33Al
Deduce Occupancy 0.17(3) of 2s1/2 only 10% cp to 36S

Since SO $\propto \nabla\rho$ see bubble structure influence SO splitting

Motivation: the 34Si bubble experiment

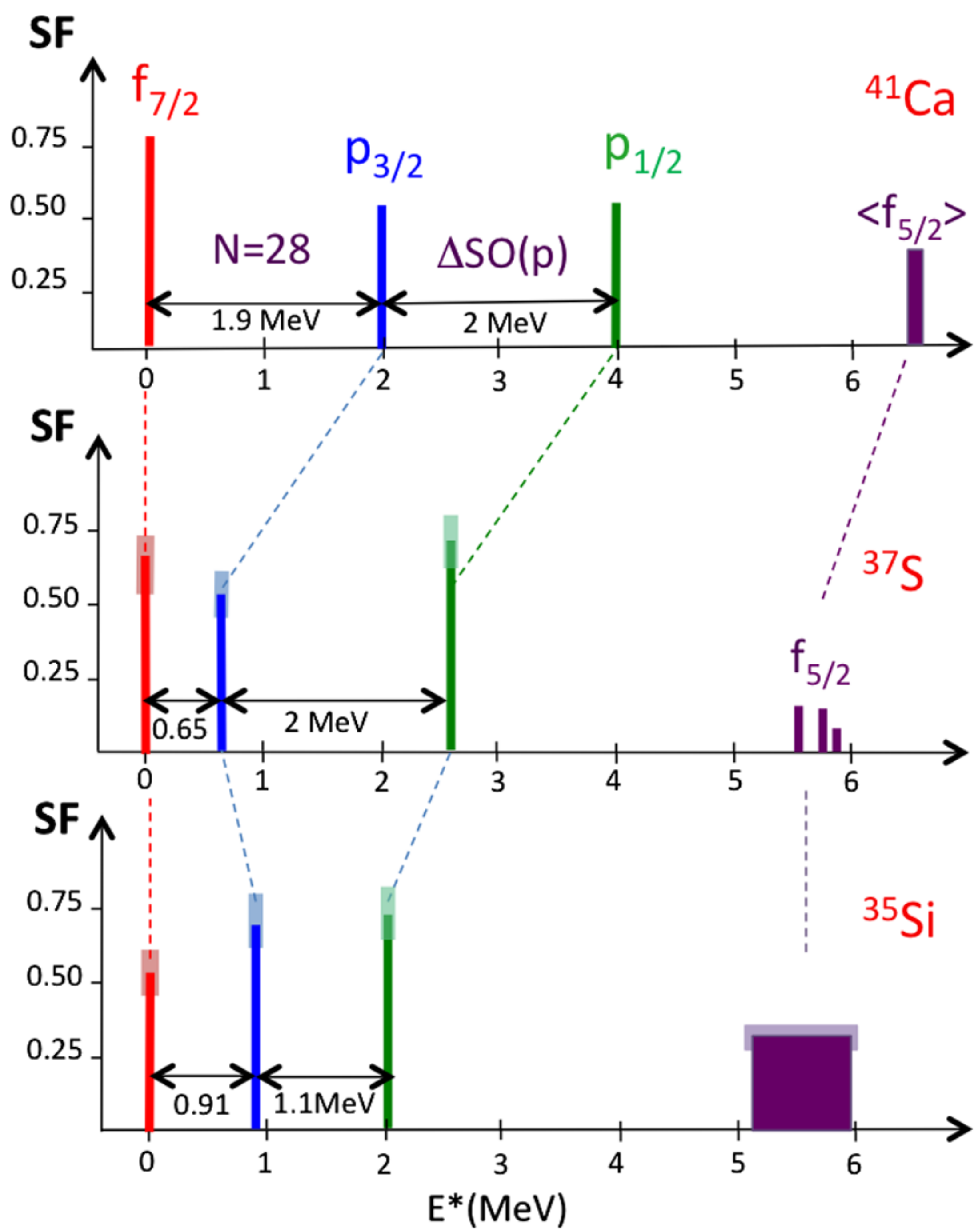


FIG. 3 (color online). Distribution of the *major* fragments of the single particle strength in ^{41}Ca (top), ^{37}S (middle), and in ^{35}Si (bottom). SF values in ^{41}Ca are taken from Ref. [29]. The centroid of the $5/2^-$ strength, obtained from a summed SF strength of 0.32, is indicated as $\langle f_{5/2} \rangle$. The SF of the $5/2^-$ components in ^{37}S are taken from [24], while all others SF are derived from the present work with error bars due to statistics and fit distributions.

Proposal:

Use the bubble structure to constrain the SO force

Experiment [Burgunder et. al. PRL **112**, 042502 (2014):

transfer reaction 34Si(d,p)35Si

Measure neutron s.p. energy with

Results:

No change in 2p splitting between 41Ca and 37S

Large reduction of 2p between 37S and 35Si

No significant change for 1f splitting

Non-Rel. calculations

[M. Grasso *et. al.* , Phys. Rev. **C 92**, 054316 (2015).]

Using skyrme-SLy5 and Gogny-D1S functionals in the MF-HF level

1.Pure Mean-Field
SO term in Mean-Field

RMF nucleons 4-cmpt Dirac spinors ψ
virtual mesons σ, ω, ϱ, (δ)
Nucleons obey Dirac equation

$$(\boldsymbol{\alpha}\cdot\boldsymbol{p}+\beta(M+S)+V)\psi_i=\varepsilon_i\psi_i,$$

Relativistic fields scalar S and vector V. (Time-rev.) $S=g_\sigma\sigma\ (+g_\delta\delta)\quad V=g_\omega\omega^0+g_\rho\tau_3\rho_3^0+eA^0.$

In non-Rel. expansion: $V_{S.O.}=\boldsymbol{W}\cdot(\boldsymbol{p}\times\boldsymbol{\sigma})$

with

$$\boldsymbol{W}=\frac{1}{2\tilde{M}^2}\boldsymbol{\nabla}(V-S)$$

effective mass

$$\tilde{M}=M-\frac{1}{2}(V-S)$$

Large S.O. term

$V-S\approx 750$ MeV

In the spherical case: $$V_{S.O.}=\frac{1}{4\tilde{M}^2}\frac{1}{r}\frac{d(V-S)}{dr}\boldsymbol{\ell}\cdot\boldsymbol{s}$$

Under approximation- zero range limit $\boldsymbol{W}_\tau=W_1\boldsymbol{\nabla}\rho_\tau+W_2\boldsymbol{\nabla}\rho_{\tau'\neq\tau}$

RMF very small isospin dep.

$$\frac{W_1}{W_2}\approx 1+2\frac{C_\rho\ (+C_\delta)}{C_\omega+C_\sigma}\quad\approx 1$$

$$C_i\ =\ g_i^2/m_i^2\quad(i\ =\ \sigma,\omega,\delta,\rho)$$

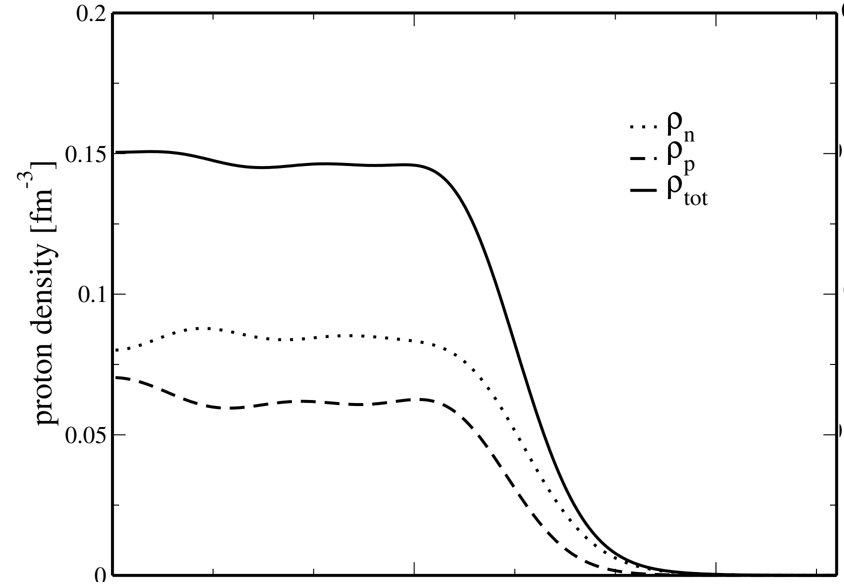
Non-Rel. strong isospin dep.

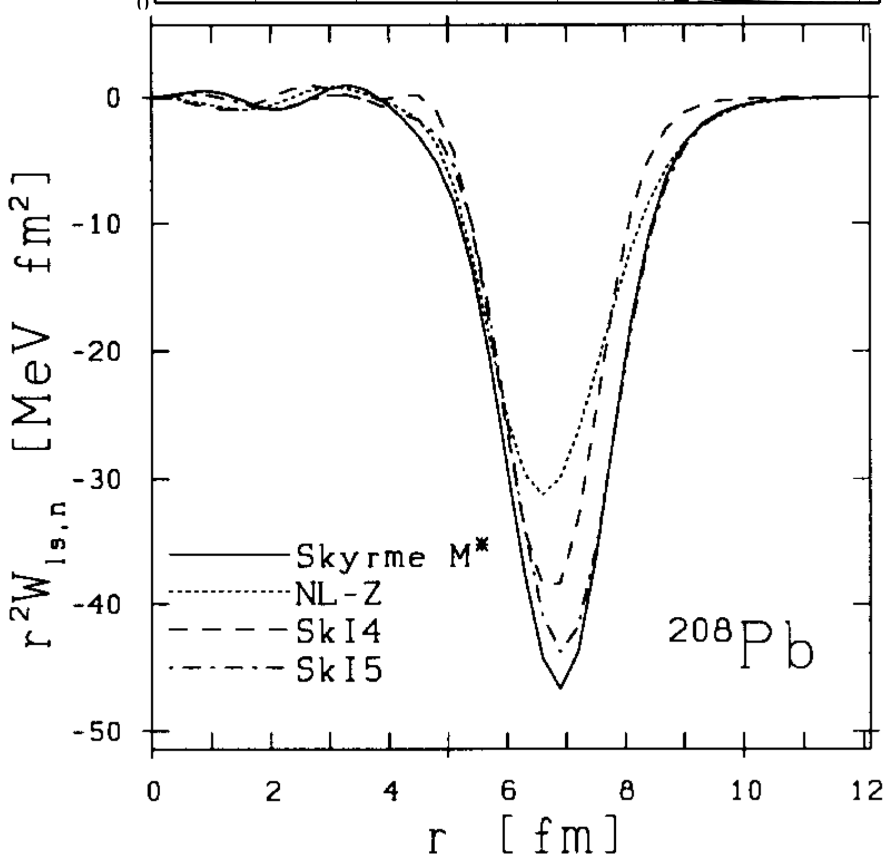
$$\frac{W_1}{W_2}=2.$$

1.Pure Mean-Field

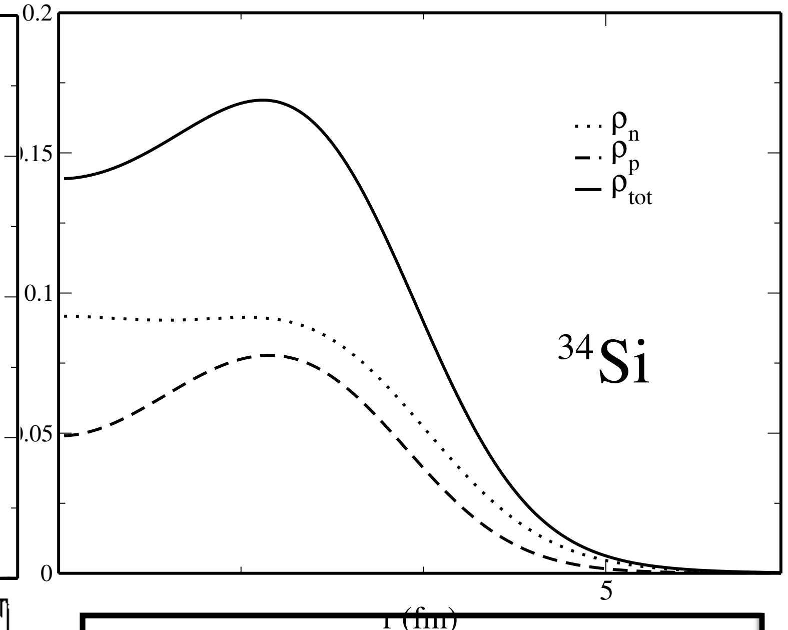
SO term in Mean-Field

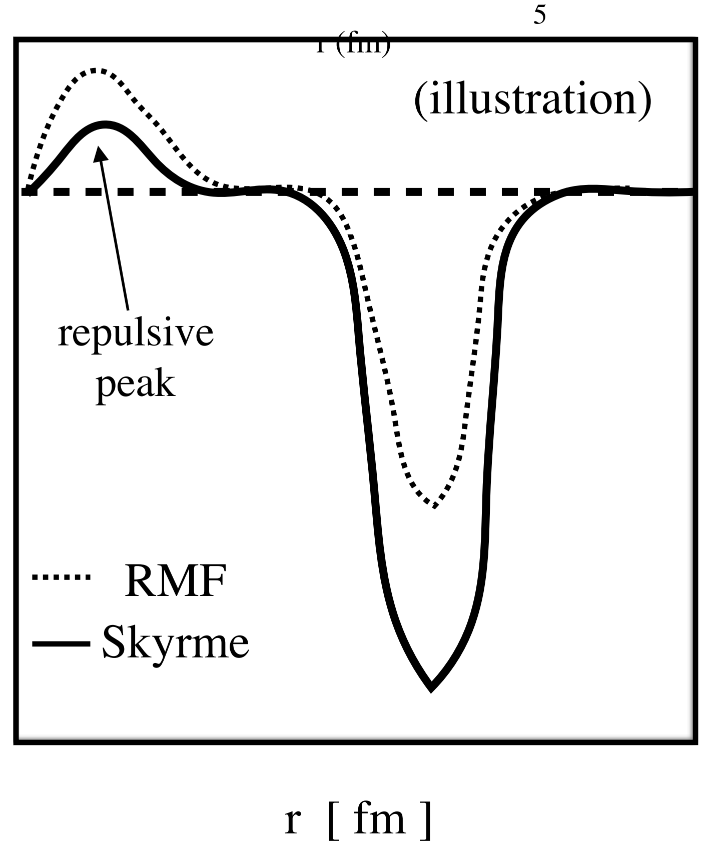
Normal





'Bubble'





Gradient $\nabla\rho$ determines the SO

<u>Most nuclei</u>

- Attractive well around the surf.
- States with large *l* most affected

Non-Rel. deeper than RMF ⟷ Larger SO splittings

<u>'Bubble' nuclei</u>

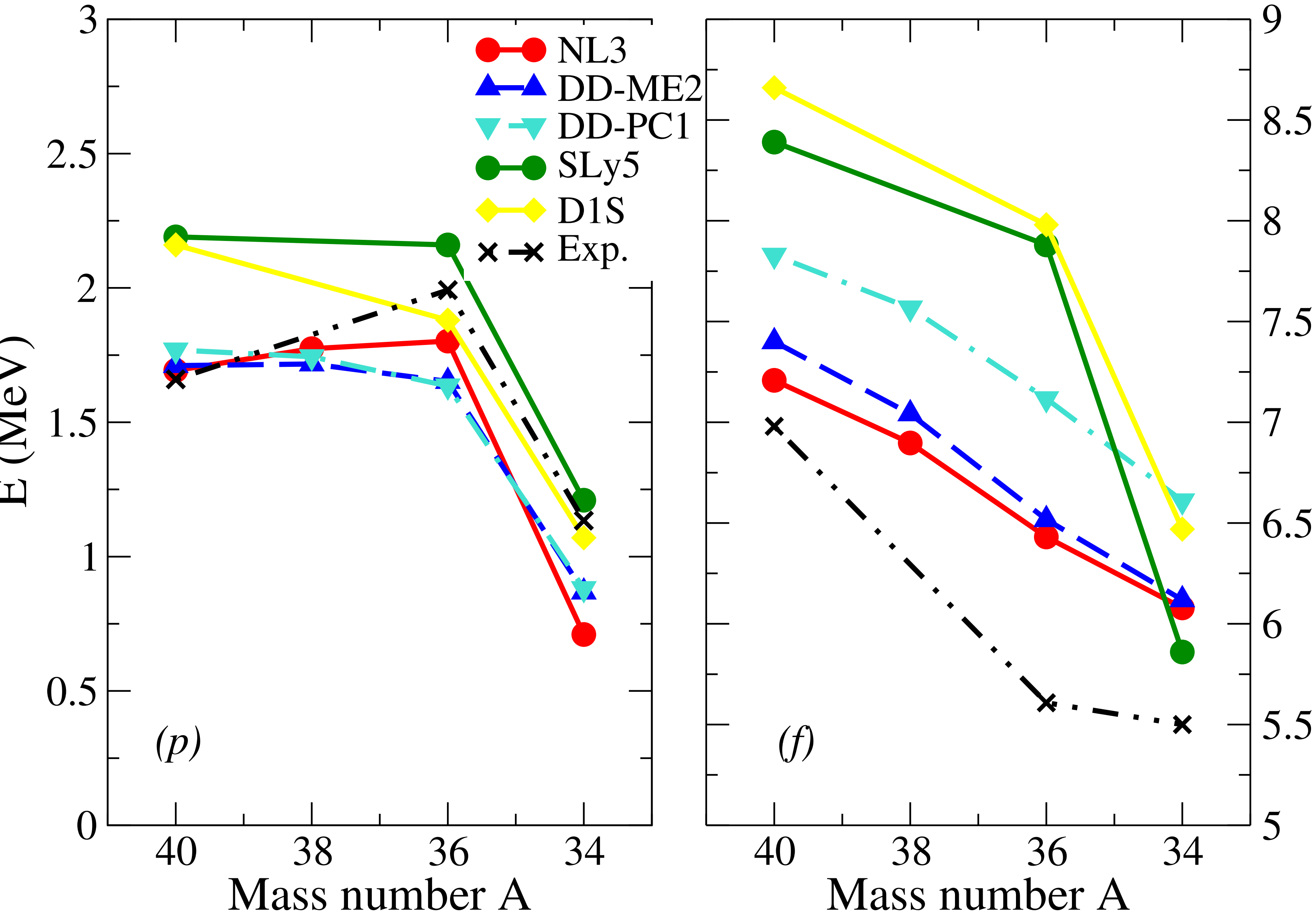
- Additional repulsive peak at center.
- States with small *l* most affected- Reduces the size of the 2p splitting

RMF larger peak ⟷ Smaller 2p Greater reduction

P.-G. Reinhard, H. Flocard / Nuclear Physics A 584 (1995) 467–488

1.Pure Mean-Field
Numerical results

Evolution of the neutron SO splittings with A



RMF results in general

- No change in 2*p* from 40Ca -> 36S
- Small, gradual reduction in 1*f* split.
- Large sudden reduction in 36S -> 34Si 'bubble'

Differences with non-Rel. and expt.

- Smaller size in all SO splittings
- *f* split. similar in 34Si because of the rel. reduction in SLy5-D1S
- Larger relative reduction of the 2*p* splitting in the 36S -> 34Si transition

2.The effect of pairing

RHB framework

Pairing correlation in proton channel of 38Ar, 36S and 34Si
Generalised Hartree-Bogolyubov framework of quasi-particles

$$\begin{pmatrix} \hat{h} - m - \lambda & \hat{\Delta} \\ -\hat{\Delta}^* & -\hat{h} + m + \lambda \end{pmatrix} \begin{pmatrix} U_k(\boldsymbol{r}) \\ V_k(\boldsymbol{r}) \end{pmatrix} = E_k \begin{pmatrix} U_k(\boldsymbol{r}) \\ V_k(\boldsymbol{r}) \end{pmatrix}$$

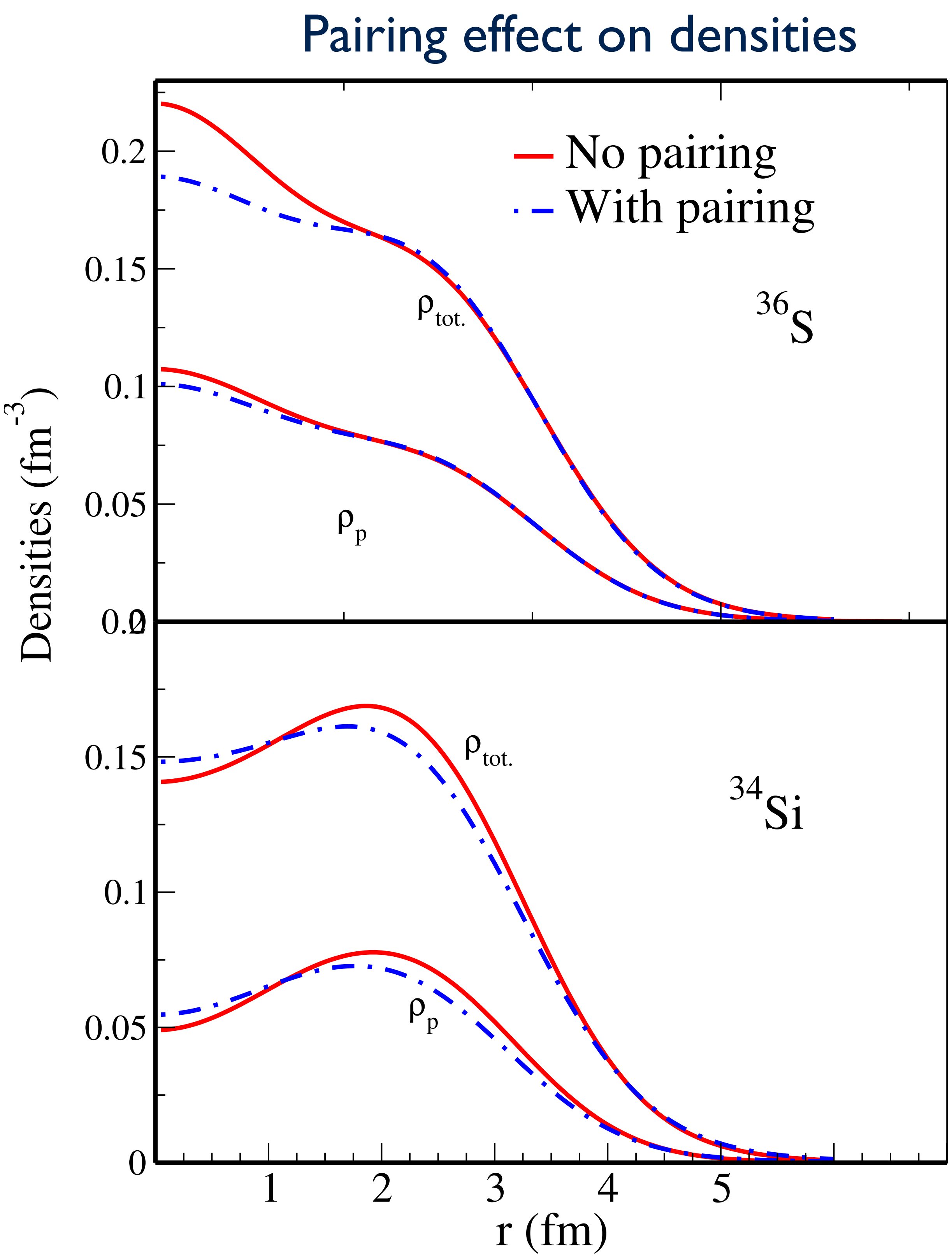
Single particle energies obtained in canonical basis
RHB equivalent to RMF + BCS

$$v_\mu^2 = \frac{1}{2}\left[1 - \frac{\varepsilon_\mu - \lambda}{\sqrt{(\varepsilon_\mu - \lambda)^2 + \Delta_\mu^2}}\right]$$

Use TMR pairing force - equivalent to Gogny finite range - avoid cutoff
Pairing strength adjusted to OES

	^{38}Ar	^{36}S	^{34}Si
$\Delta_C^{(3)}$(MeV)	0.93	0.45	1.95

2.The effect of pairing
Proton densities

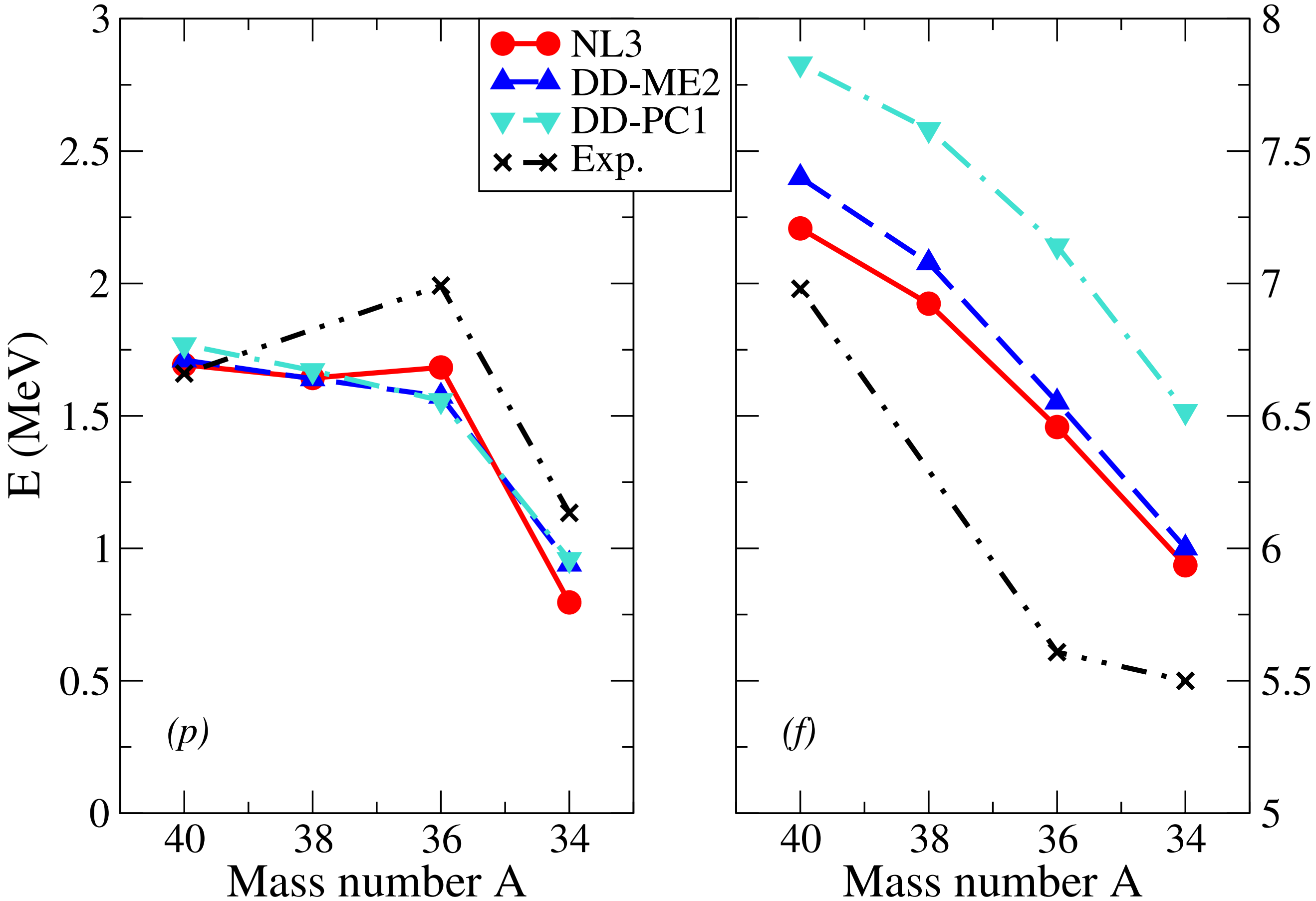


- Occupancy of *2s1*/2: decreased in 36S
  increased in 34Si
- Larger surface diffusion
- Smoothening of the Bubble structure

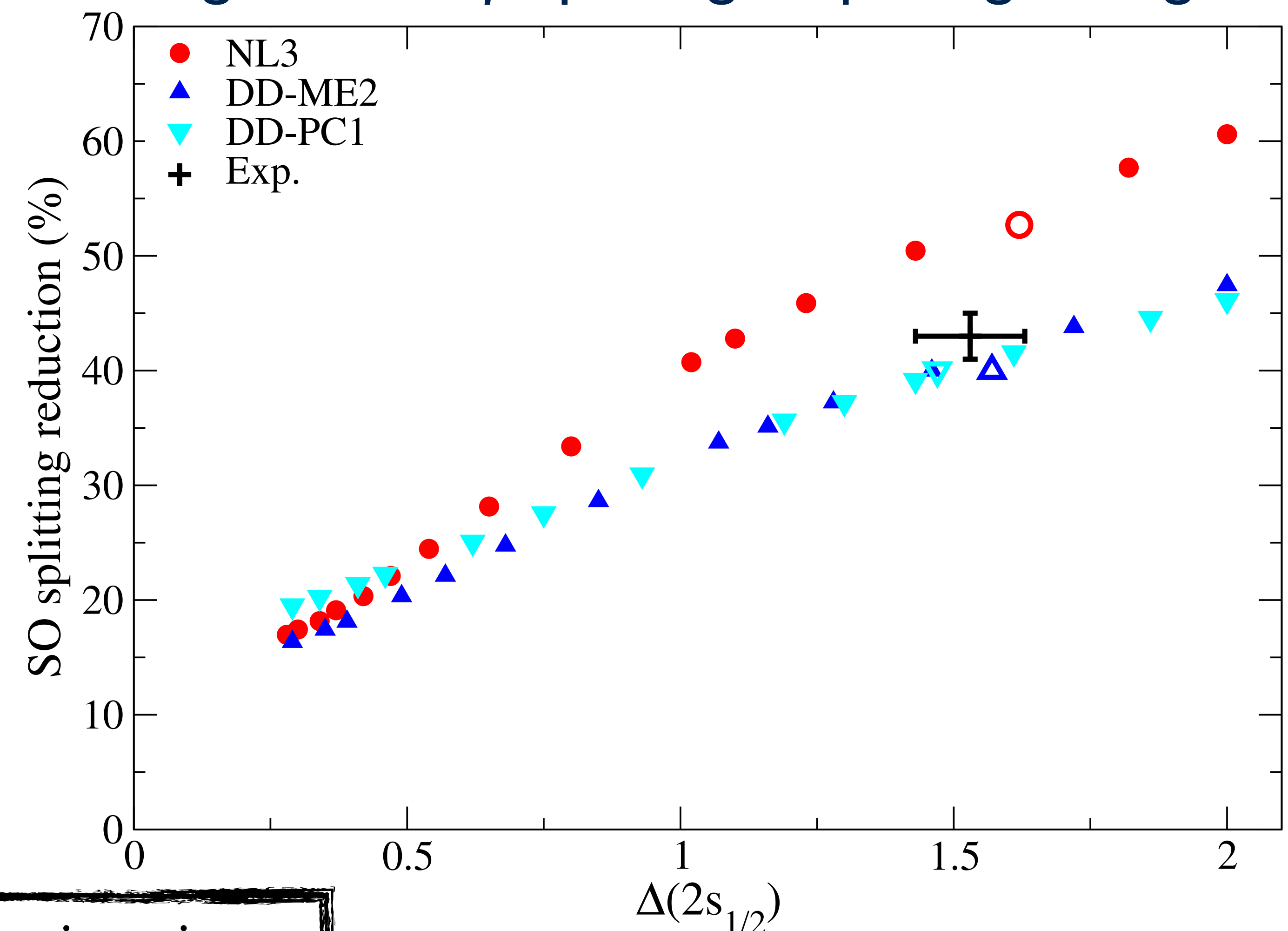
2.The effect of pairing

Numerical results

Evolution of the neutron SO splittings with A



Change of the 2p splitting wt pairing strength



Same qualitative picture

The inclusion of pairing

- In 38Ar and 36S increases *f* and reduces p splitting
- In 34Si reduces *f* and increases *p*, due to smaller central depletion

Connection bt relative *p* reduction and $\Delta(2s_{1/2})$

- Stronger pairing, smaller occupancy change, smoothening of 'bubble' -> Smaller relative *p* reduction 36S -> 34Si

3.The effect of the Tensor
One pion exchange (OPE)

Rel. Hartree $\longrightarrow$ Relativistic Hartree-Fock

G.A Lalazissis *et. al*. PRC80, 041301(R)(2009)

Add two terms corresponding to (OPE) dynamics

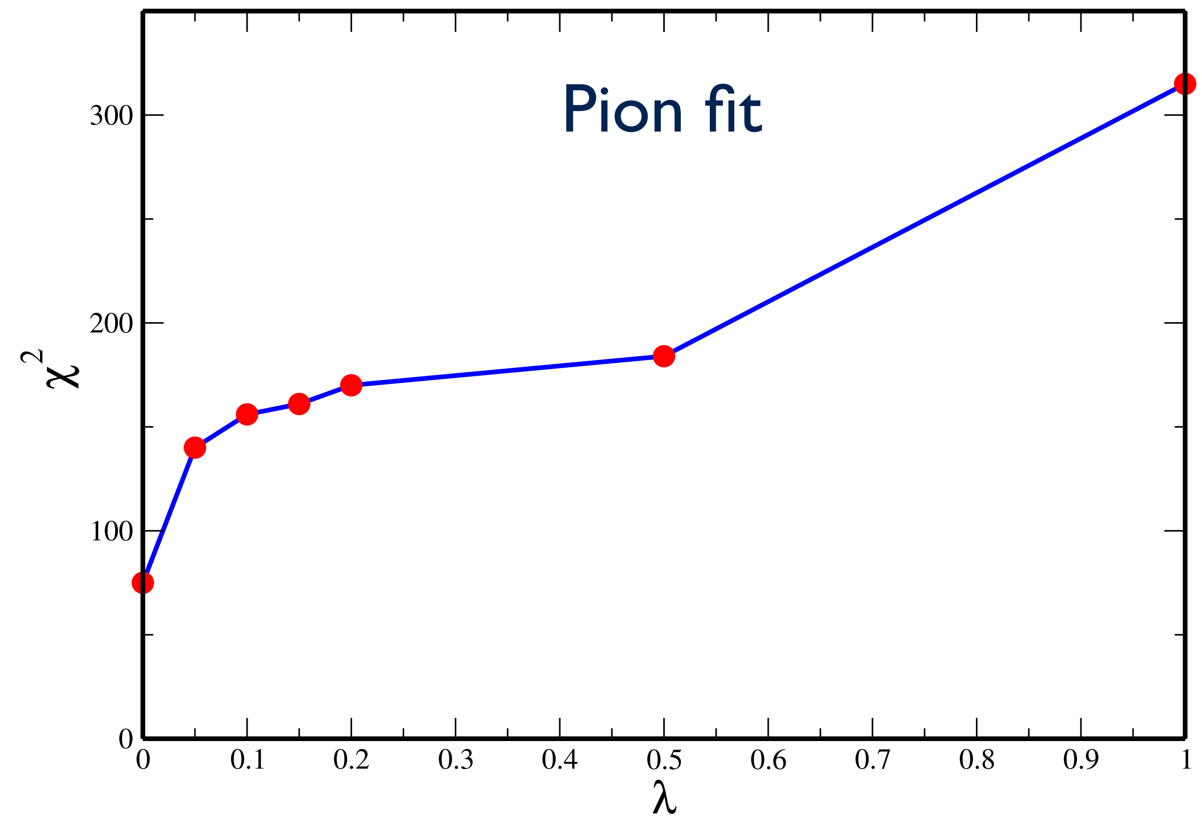
$$\mathcal{L}_\pi = \frac{1}{2}\left(\partial_\mu\vec{\pi}\partial^\mu\vec{\pi} - m_\pi^2\right)\vec{\pi}^2$$

$$\mathcal{L}_{pv} = -\frac{f_\pi}{m_\pi}\bar{\psi}\gamma_5\gamma_\mu\partial^\mu\vec{\pi}\vec{\tau}\psi$$

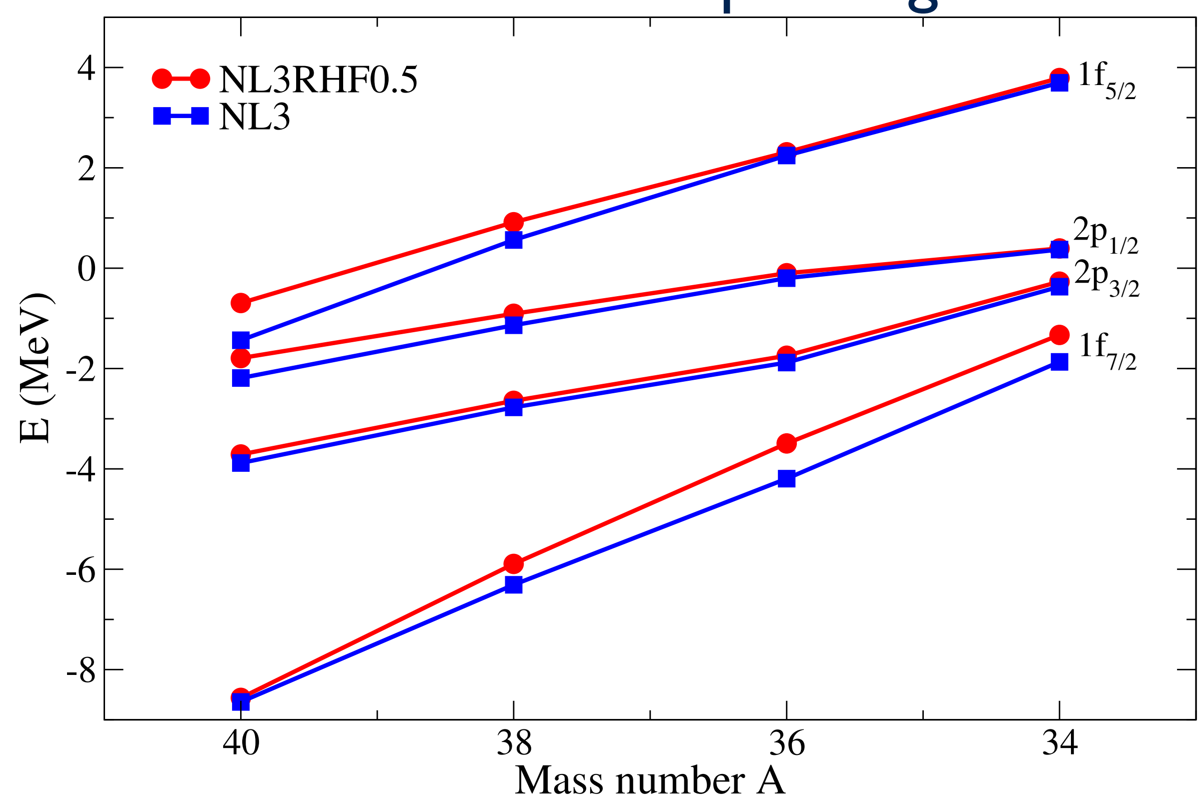
$$f_\pi^2 = \lambda f_\pi^{2free}$$

- $\lambda = 0$: Optimal refit incl. OPE of NL3
- $\lambda = 0.5$: reproduces certain expt data of s.p. structure in Sn isotopes
- effect of tensor force bt neutrons and protons

determined by spin-orbit alignment
antiparallel spins $\longrightarrow$ attraction
parallel spins $\longrightarrow$ repulsion

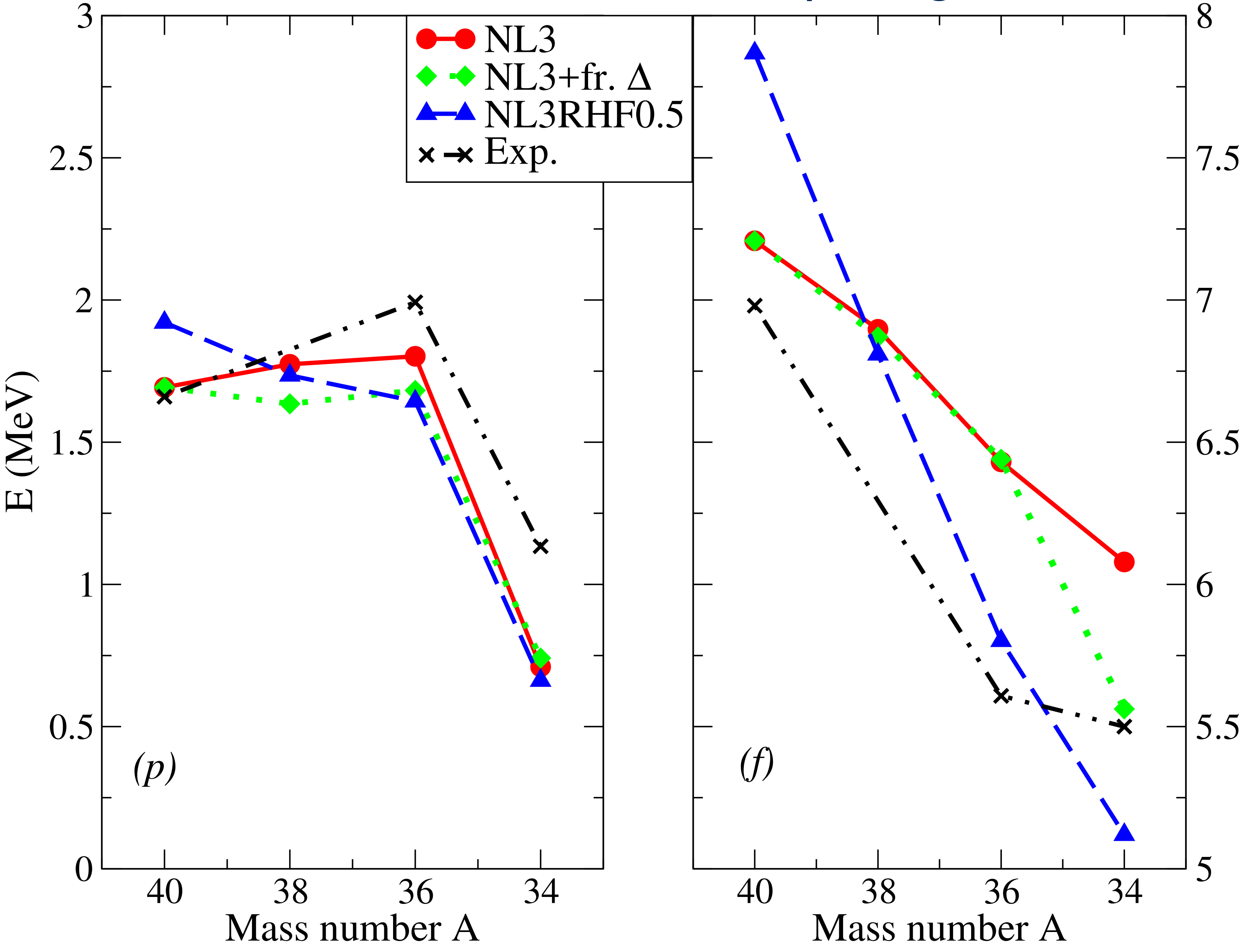


Tensor effect on s.p. energies



3.The effect of the Tensor
Numerical results

Evolution of the neutron SO splittings with A



Comparison with RH

40Ca ⟶ 36S

Enhanced quenching of the *f* and *p* spl.

36S ⟶ 34Si

f splitting much smaller

p spl. slightly decreased - Pure SO eff.

A frozen gap approximation for pairing

Occupancy of 2*s*1/2 in 34Si g.t. RH

Opposite effect than pairing

4.The effect of Particle Vibrational coupling-(PVC)

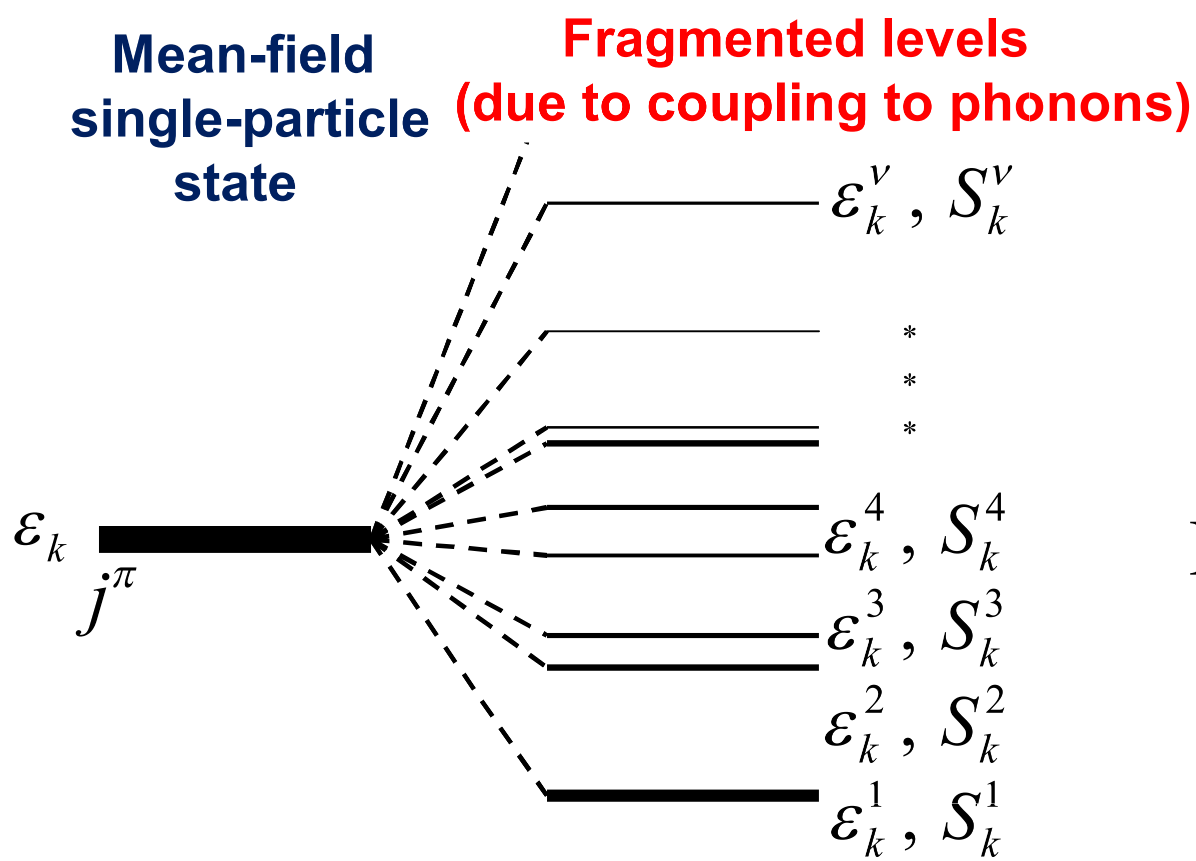
1st step static DFT   2nd step collective vibrations

PVC induces energy dependence on eff. potential

$$\Sigma = S + V + \Sigma(\omega)$$

ω phonon frequency

Mean field   Pole part

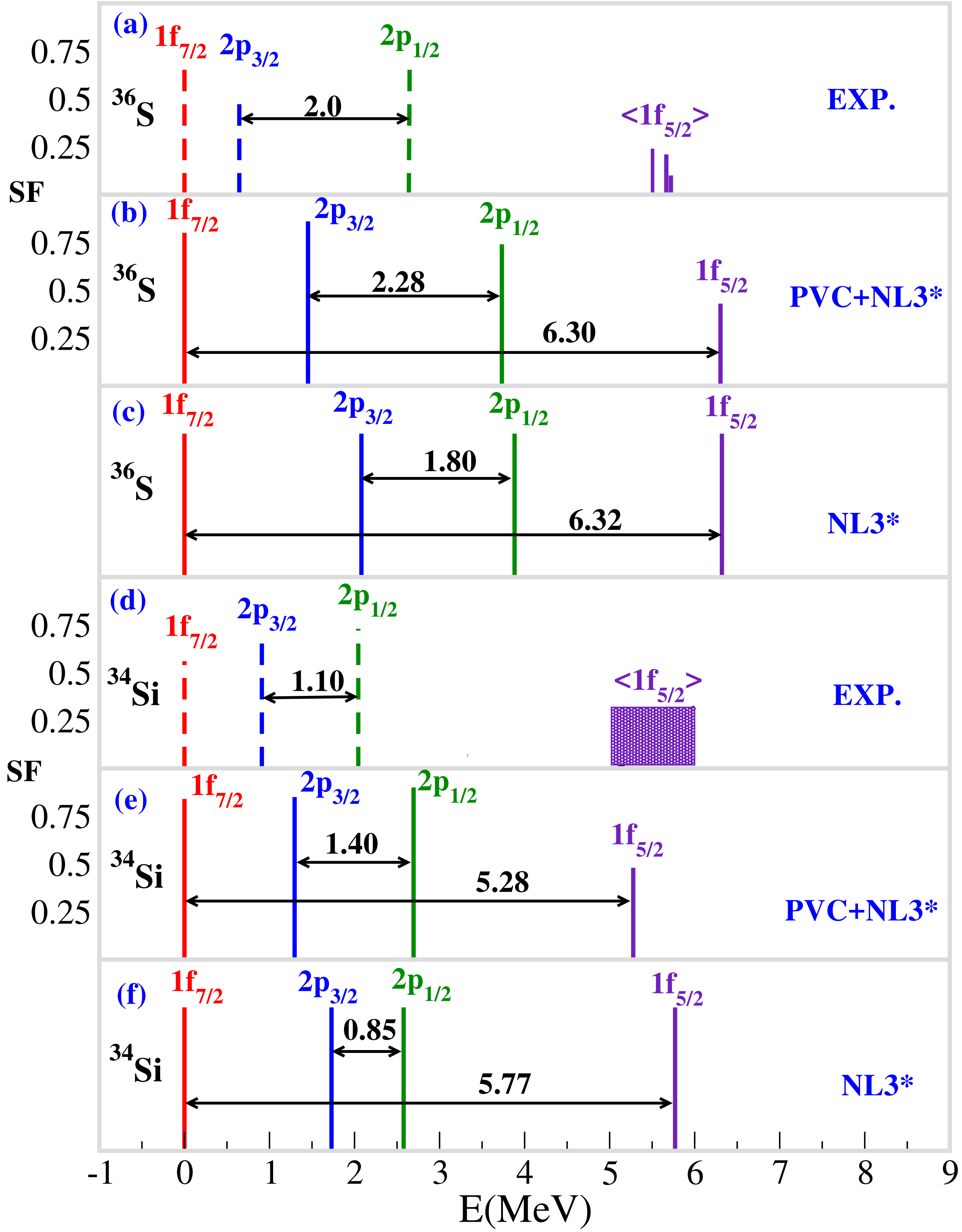


Denser spectrum

S_k^{ν} Single particle strength, sum rule: $\sum_{\nu} S_k^{\nu} = 1$

4. The effect of Particle Vibrational coupling

Numerical Results



Direct comparison with expt.
major fragments

No big effect on 1*f* splitting

2*p*-orbits shifted downwards
more for orbits close to fermi
increase in the size

rel. reduction closer to expt.

Conclusions

- In general the observed qualitative picture is reproduced
  - Large sudden reduction on 2*p* splitting going to the ‘bubble’
  - No significant change otherwise
- Smaller isospin dependence leads to smaller SO splitting than non-Rel.
- Quantitatively relative reduction larger than expt.
- Pairing correlations correct for that
- Tensor effects mainly 1*f*, showing the pure SO character of the 2*p* reduction, acts opposite than pairing
- PVC improves the qualitative picture.
  - Shifts the 2*p* orbits in the correct direction
  - *2p* Relative reduction in 36S $\longrightarrow$ 34Si closer to experiment