Neutron-proton spin-spin correlations in $N = Z$ nuclei

P. Van Isacker, GANIL, France

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$T = 1$ and $T = 0$ pairing correlations

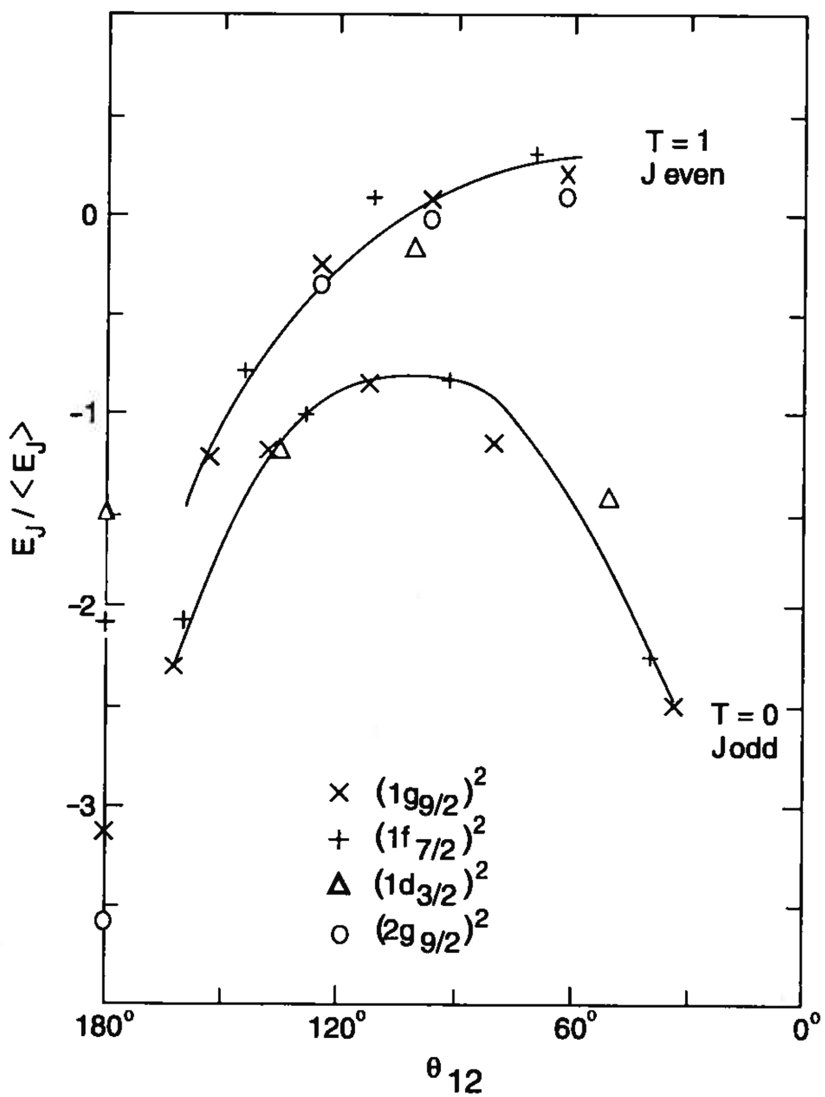
- General considerations
- What is the question?
- Pair vibrations

Neutron-proton spin-spin correlations

Conclusion and outlook

ESNT, Saclay, December 2024

Nucleon-nucleon interaction



J.P. Schiffer, Ann. Phys. (N.Y.) **66** (1971) 798

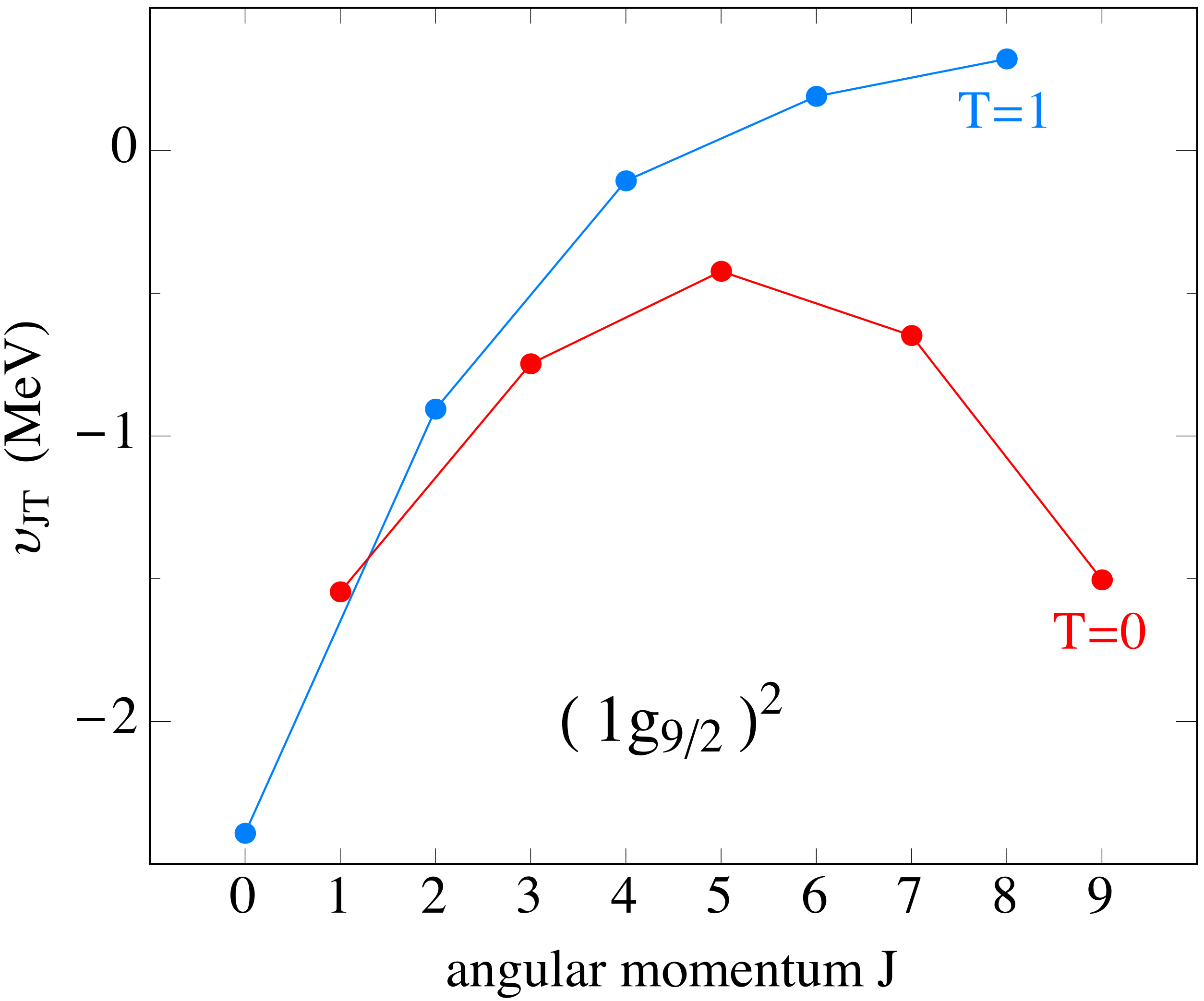
Pairing and other interactions

Pairing refers to the interaction between nucleons in 'time-reversed orbits':

- *isovector (or spin-singlet) pairing: J=0 & T=1*
- *isoscalar (or spin-triplet) pairing: J=1 & T=0*

Aligned np interaction (**not**) pairing): $J=2j$ & $T=0$

Nucleon-nucleon interaction



Time-reversed orbits

A jj-coupled two-nucleon state with angular momentum $J = 0$:

$$\left|j^2;J=0\right\rangle \propto \sum_{m_j} \left\langle jm_j\ j-m_j \middle| 00\right\rangle \left|jm_j\right\rangle \left|j-m_j\right\rangle \propto \sum_{m_j} \left|jm_j\right\rangle \left|j\bar{m}_j\right\rangle$$

What about $J = 1$? Use LS-coupled states:

$$\left|(\ell s)^2;L=0,SM_S\right\rangle \propto \sum_{m_\ell m_s m'_s} \left\langle sm_s\ sm'_s \middle| SM_S\right\rangle \left|\ell m_\ell;sm_s\right\rangle \left|\ell\bar{m}_\ell;sm'_s\right\rangle$$

The Pauli principle allows $(L = 0, S = 0, T = 1)$ and $(L = 0, S = 1, T = 0)$ ➔ two pairing interactions.

A matter of strength

Relation between jj-coupled and LS-coupled matrix elements:

$$V\left(j^2;JT\right) = \sum_{LS} \begin{bmatrix} \ell & s & j \\ \ell & s & j \\ L & S & J \end{bmatrix}^2 V\left[\left(\ell s\right)^2;LST\right]$$

For pairing matrix elements:

$$V\left(j^2;J=0,T=1\right) \approx \frac{1}{2} V\left[\left(\ell s\right)^2;L=0,S=0,T=1\right]$$

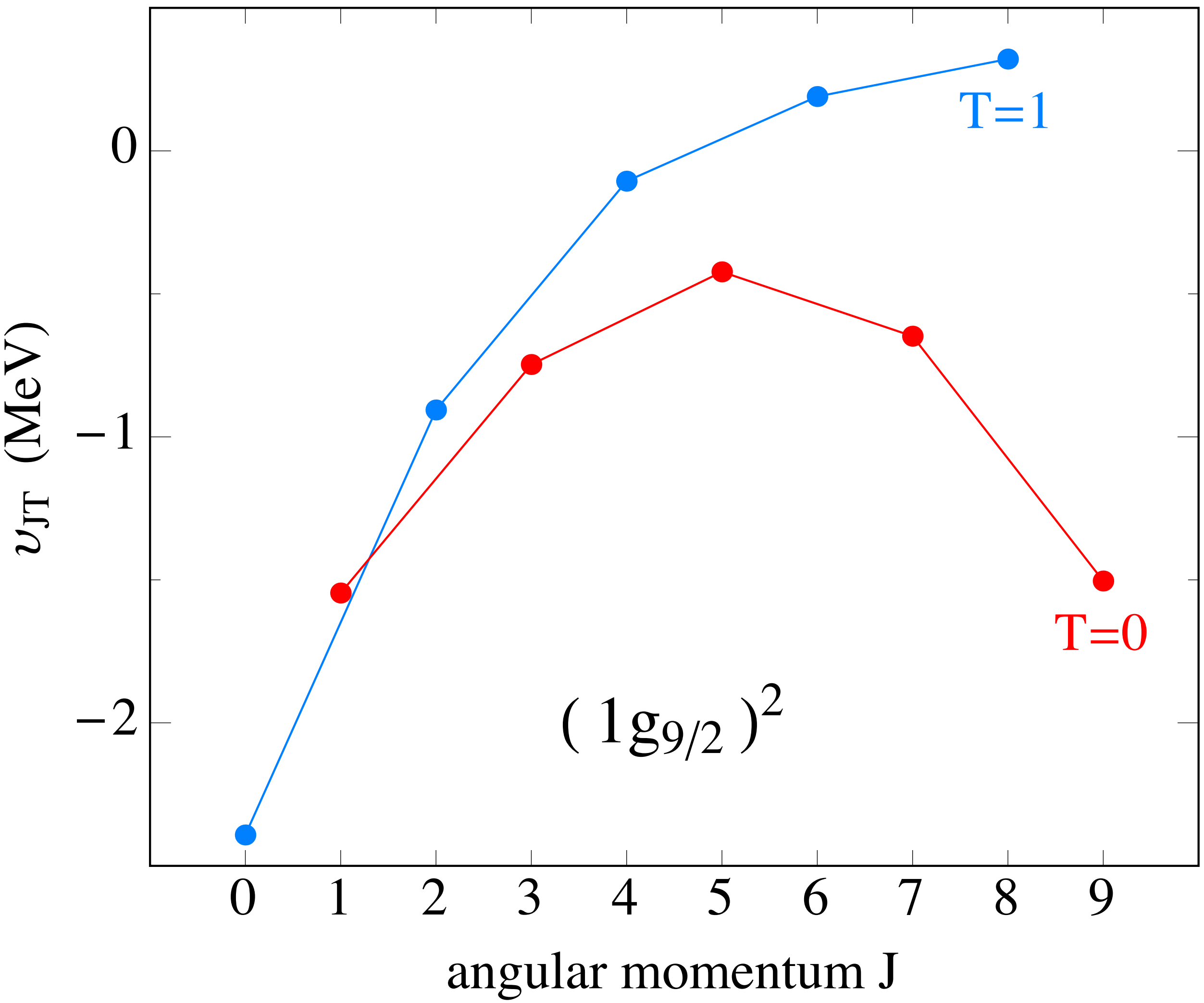
$$V\left(j^2;J=1,T=0\right) \approx \frac{1}{6} V\left[\left(\ell s\right)^2;L=0,S=1,T=0\right]$$

What is the question?

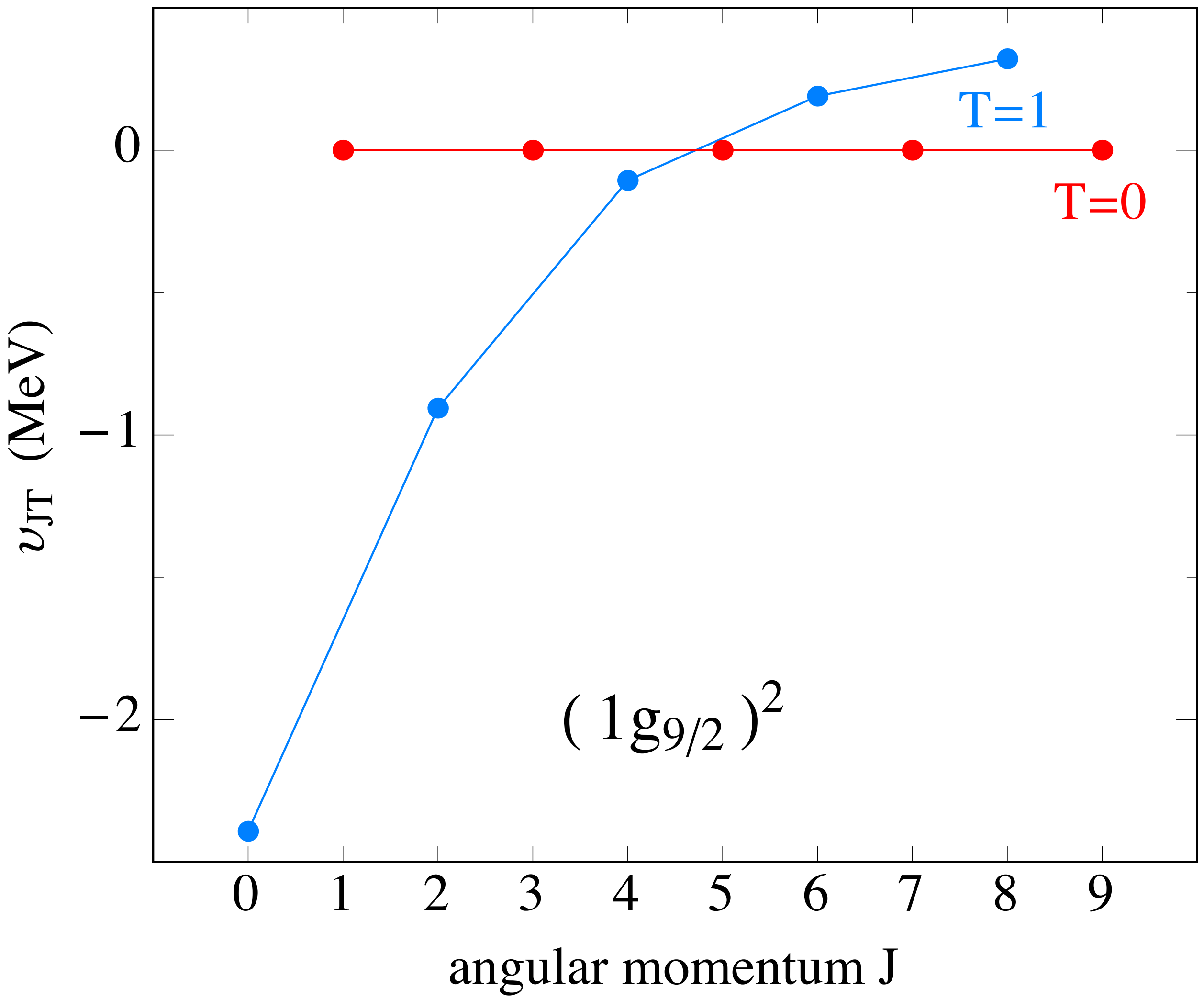
The question is **<u>not</u>** whether $T = 0$ interactions between nucleons exist or whether they are important.

They do exist and they are important.

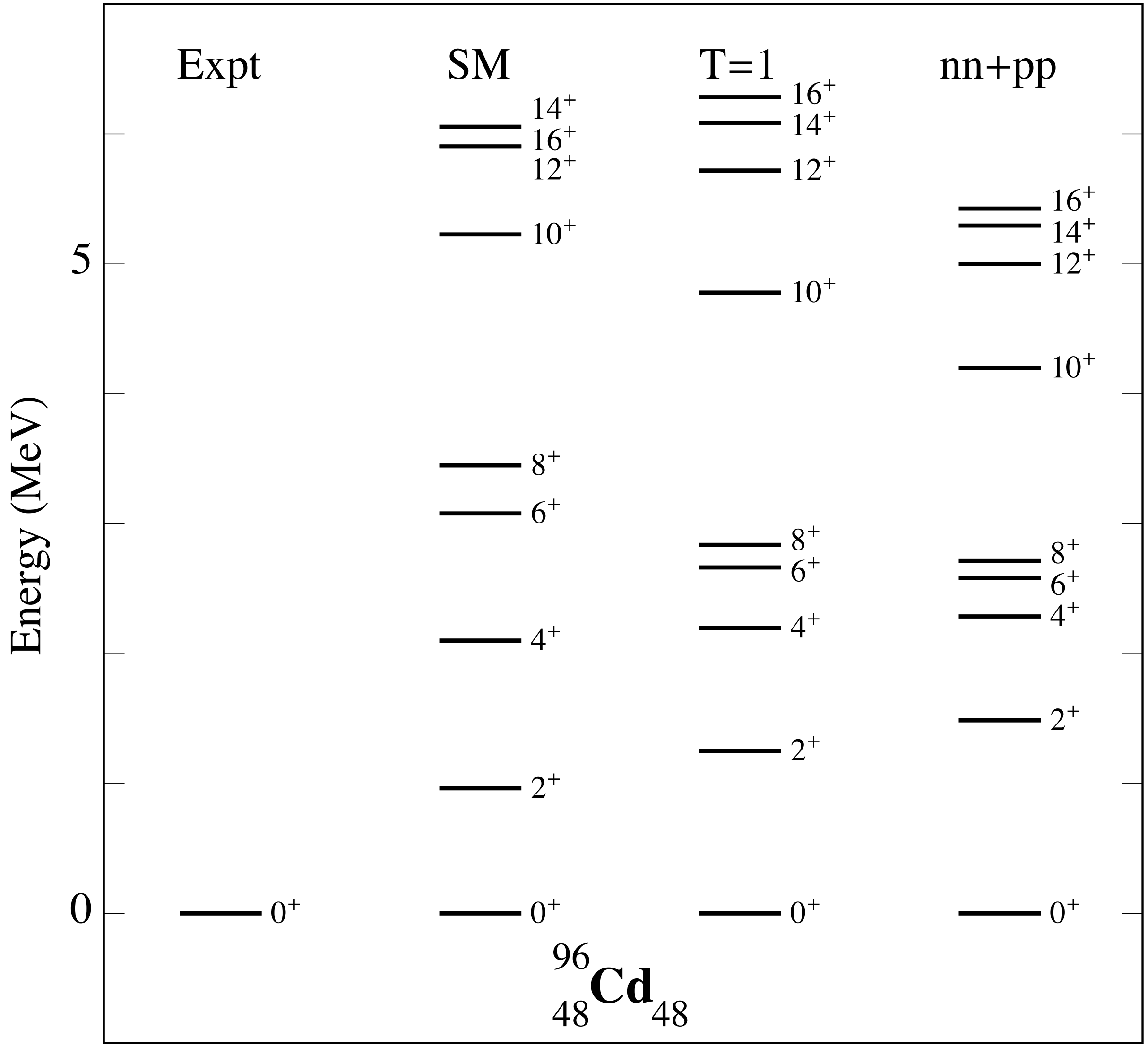
This is not the question



This is not the question



This is not the question



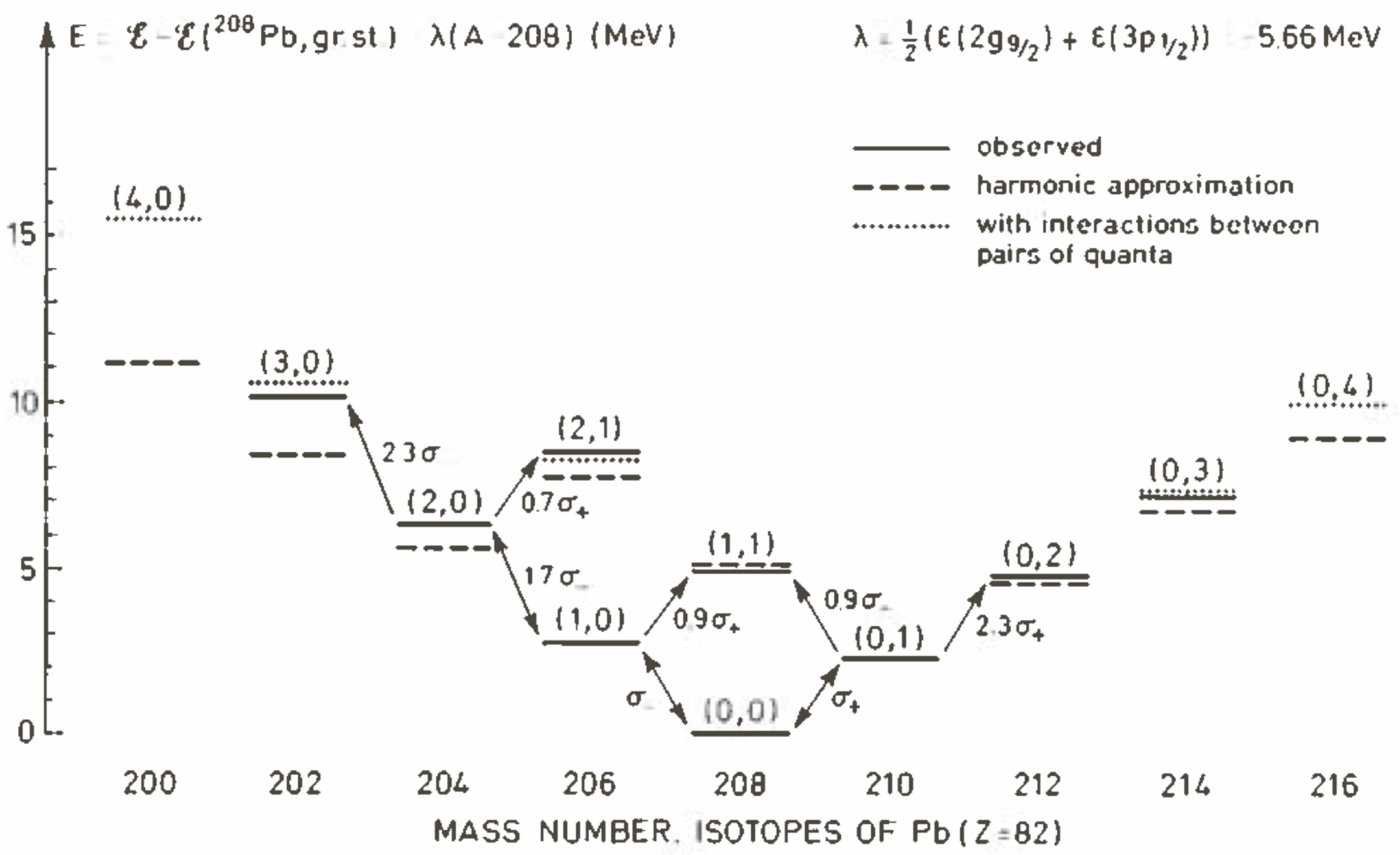
What is the question?

The question is <u>**not**</u> whether $T=0$ interactions between nucleons exist or whether they are important. They do and they are.

The question is

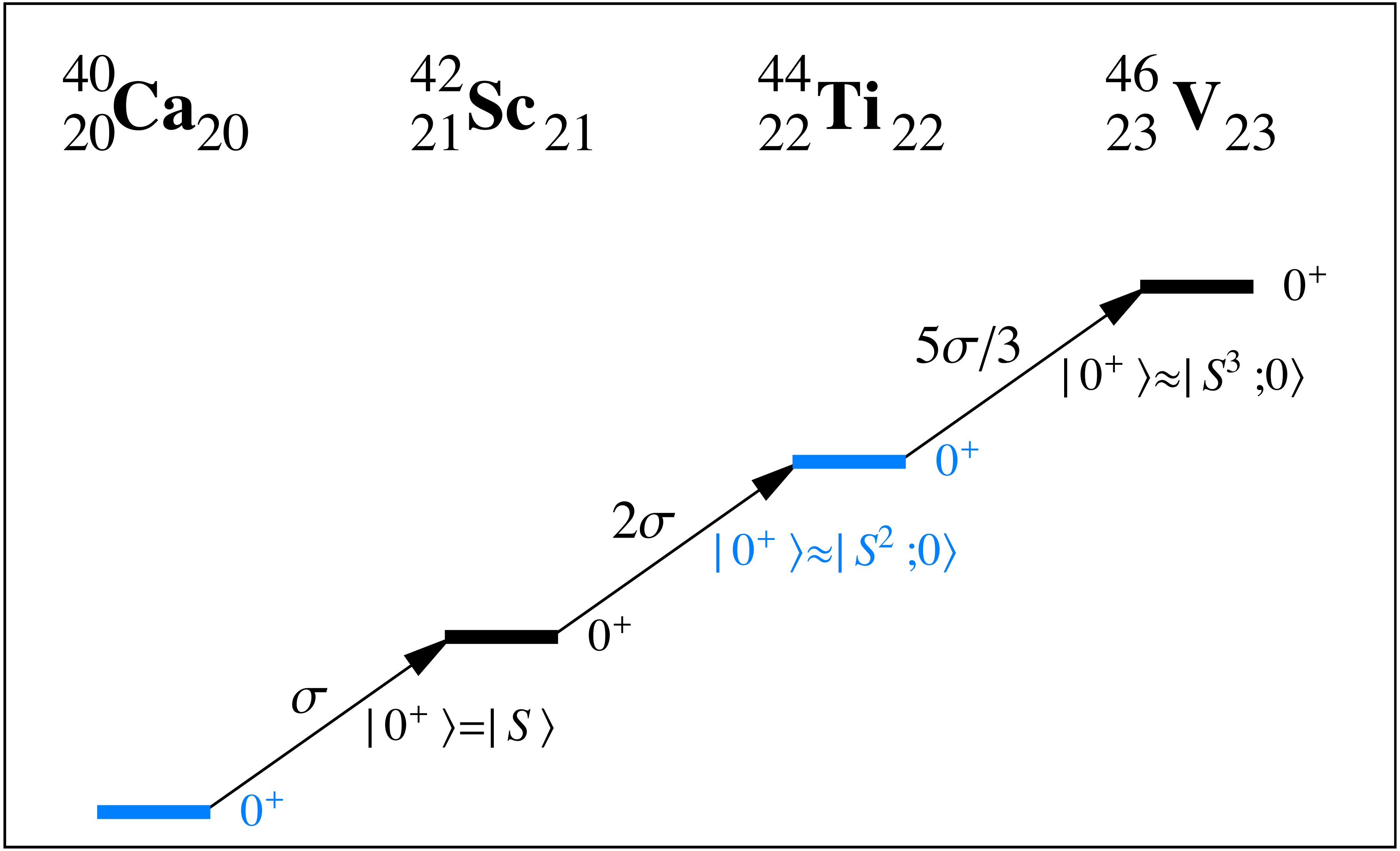
- *Do* $T=1$ *pairing correlations exist?*
- *Do* $T=0$ *pairing correlations exist?*
- *Are aligned* $T=0$ *pairs important?*
- *Do quartet correlations exist?*

T=1 pair vibrations in Pb

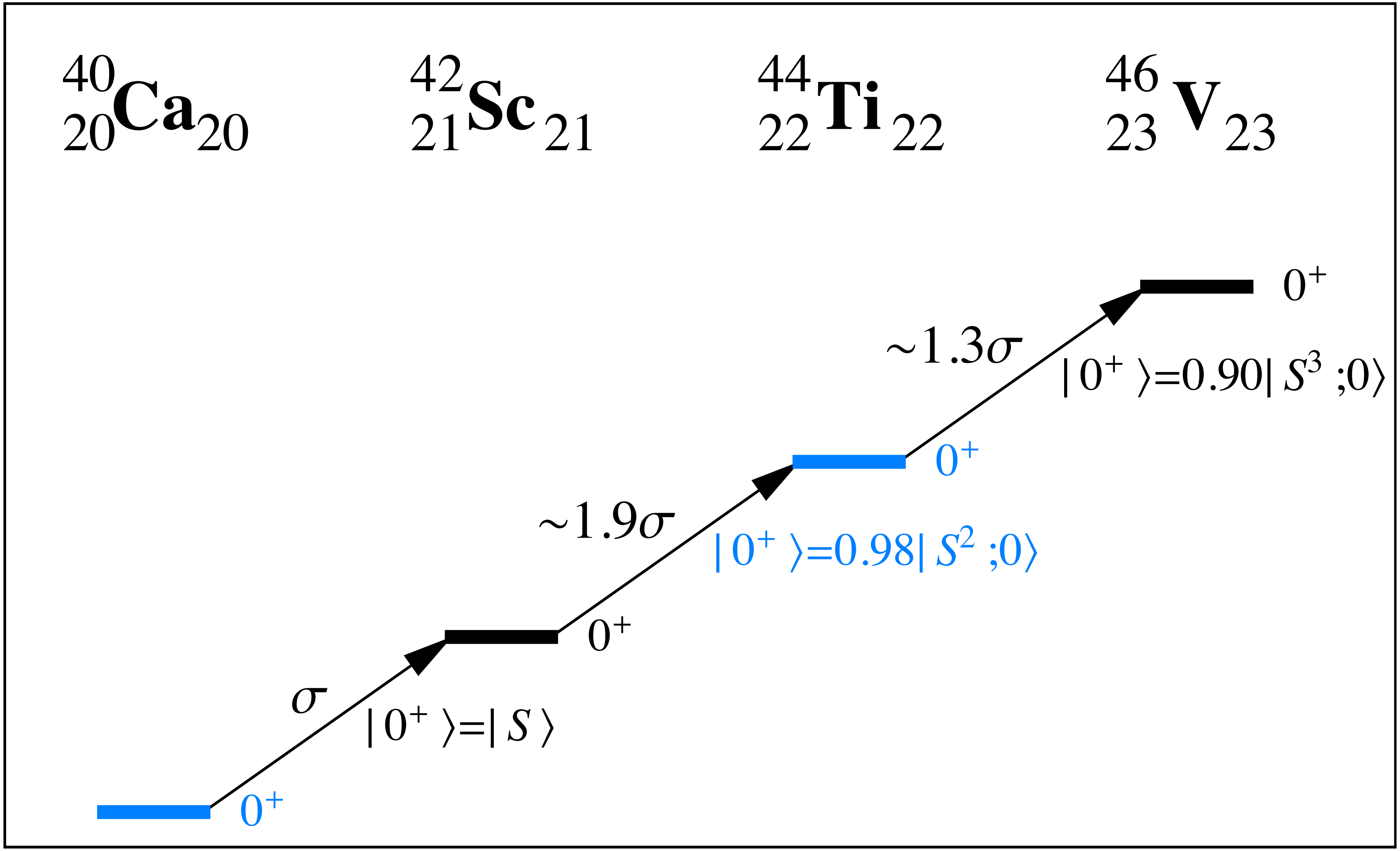


A. Bohr & B.R. Mottelson, Volume 2, page 646

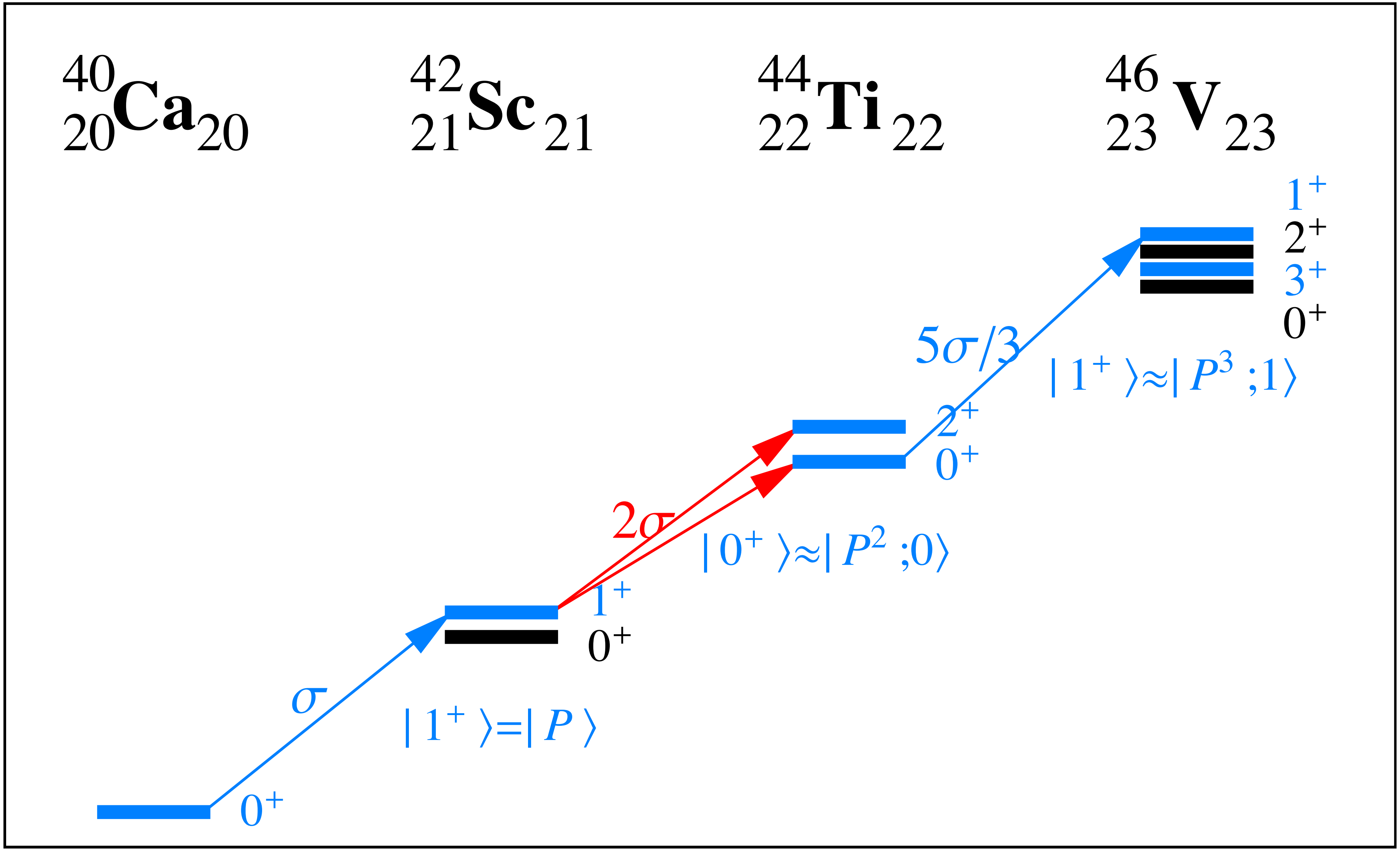
T=1 pair vibrations in Ca-Sc-Ti-V?



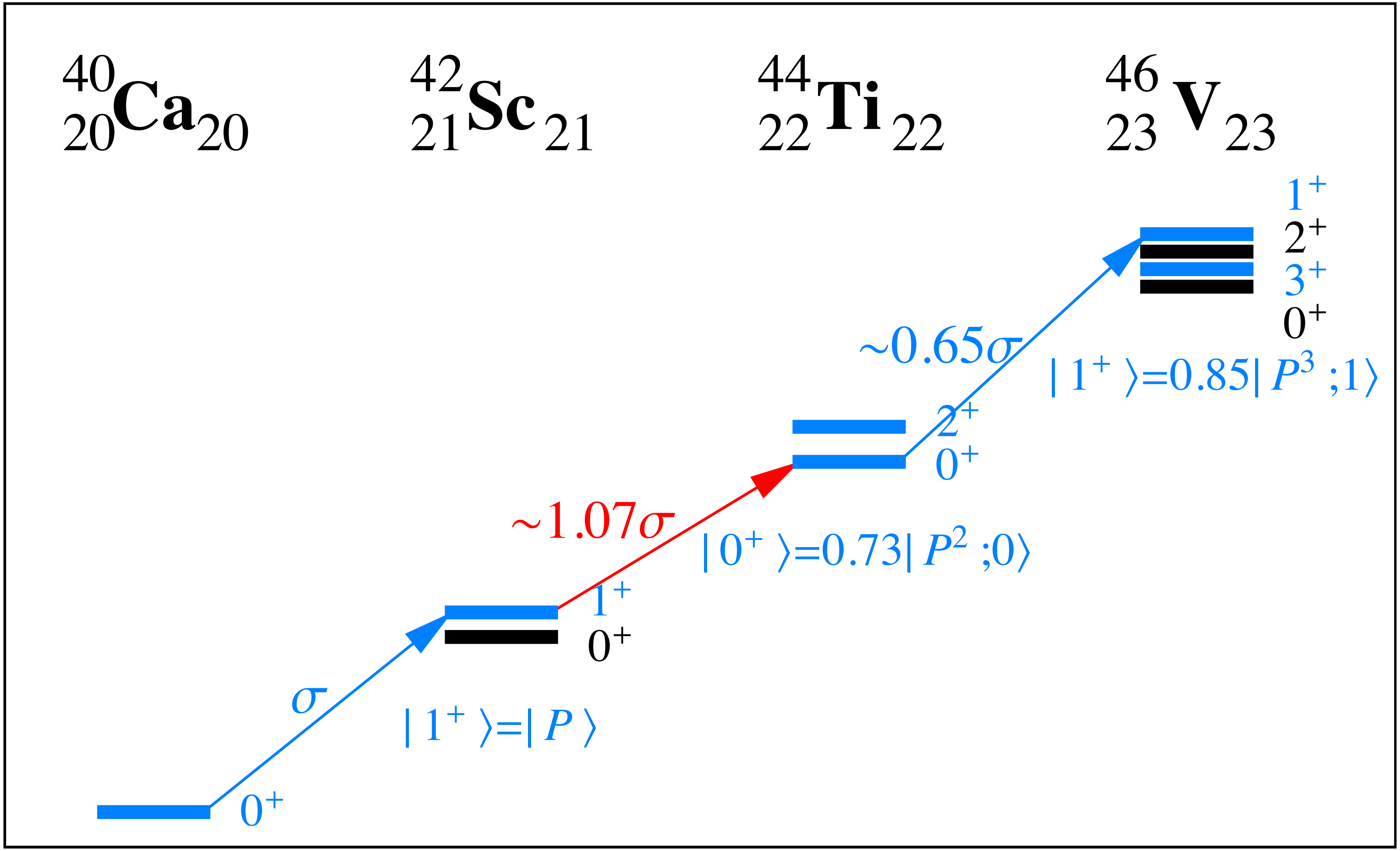
T=1 pair vibrations in Ca-Sc-Ti-V?



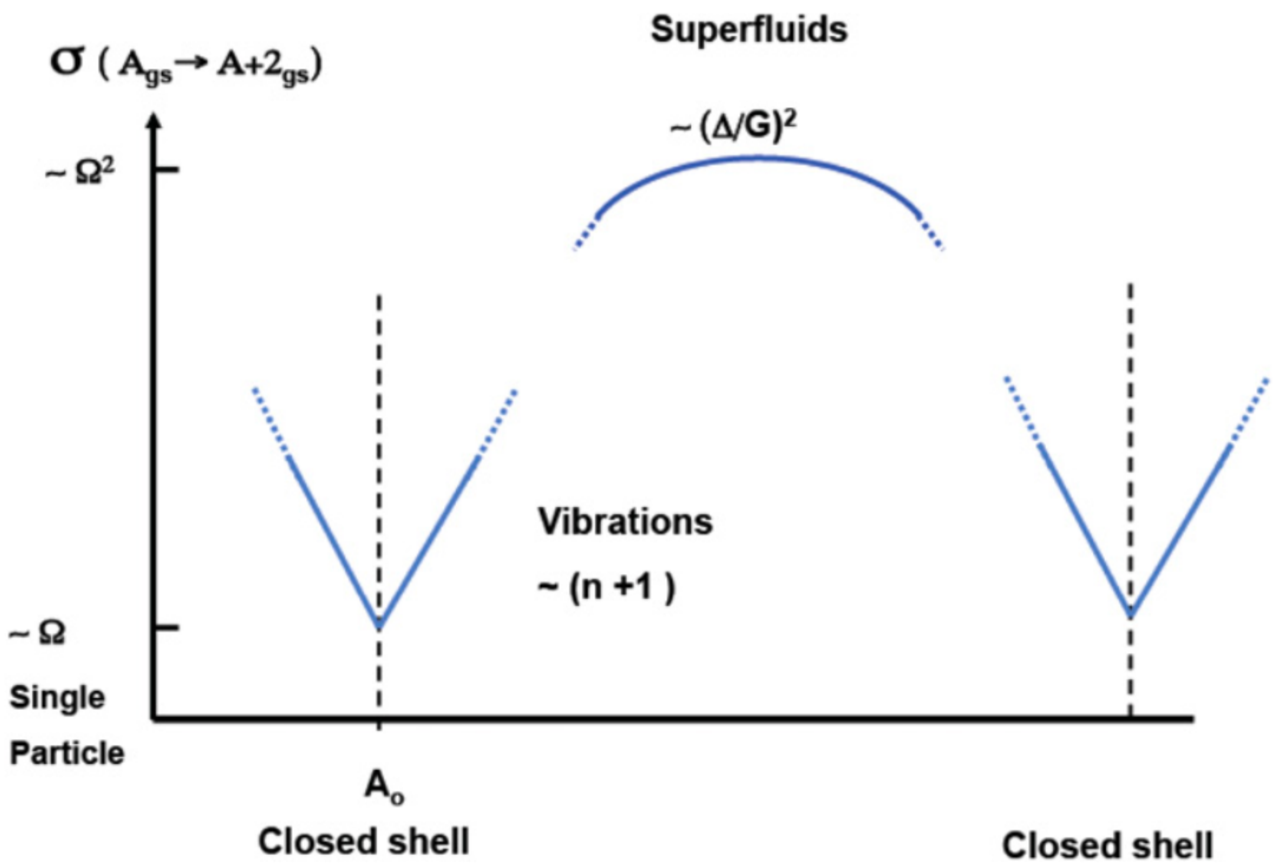
T=0 pair vibrations in Ca-Sc-Ti-V?



T=0 pair vibrations in Ca-Sc-Ti-V?

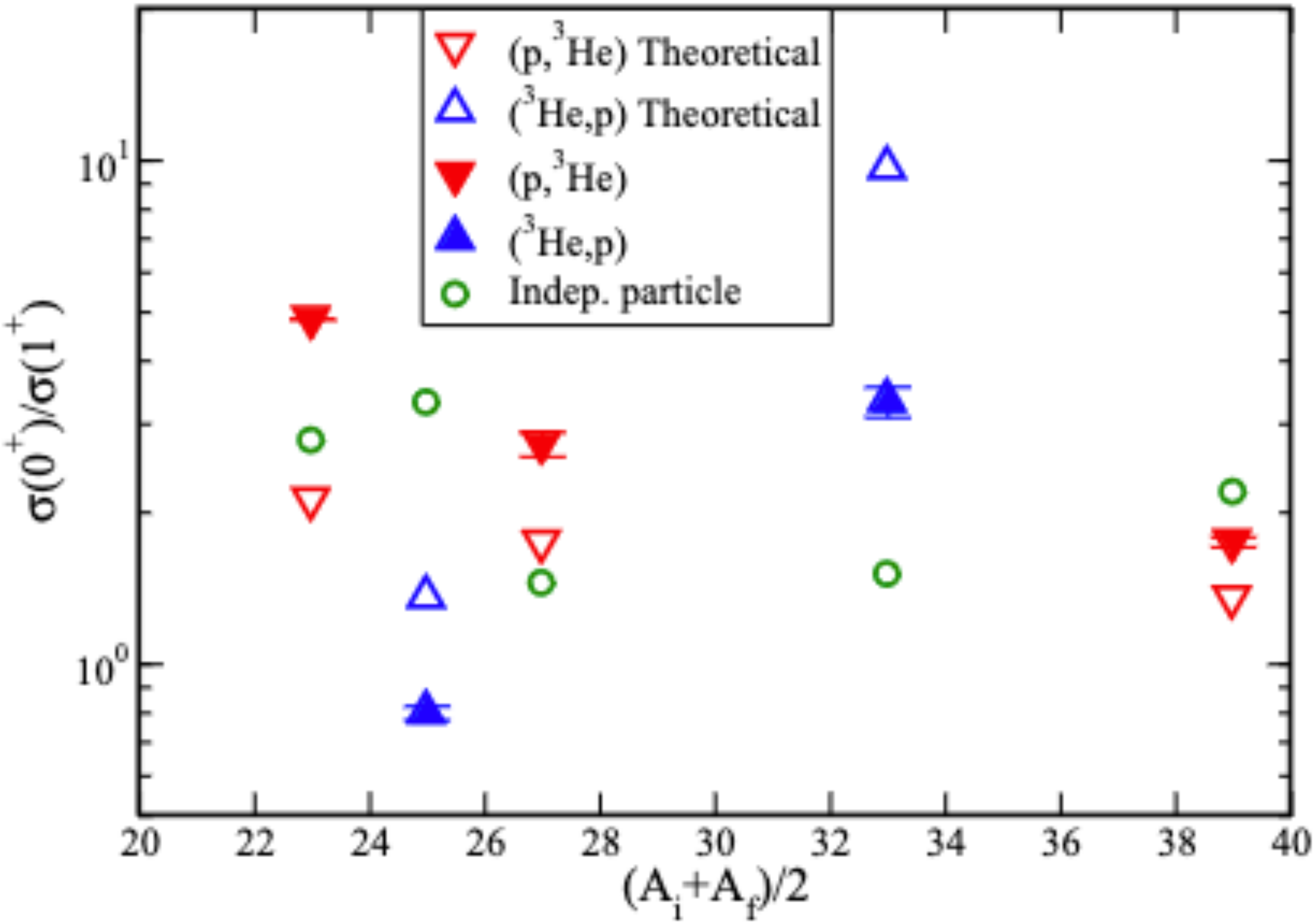


From vibrations to rotations



S. Frauendorf, A.O. Macchiavelli, Prog. Part. Nucl. Phys. **78** (2014) 24

$(p,^3He)$ and $(^3He,p)$ in *sd* shell



Y. Ayyad *et al.*, Phys. Rev. C **96** (2017) 021303R

(d,^{4}He) and (p,^{3}He) in $f_{7/2}$ shell

GANIL

PROPOSAL FOR EXPERIMENT

PAC date :	EXP # (Do not fill in):
November, 2011	E

TITLE : Study of n-p pairing through two-nucleon transfer reactions

Is it a follow up experiment? [Yes/No]: If yes, experiment number: E

Spokespersons (if several, please use capital letters to indicate the name of the contact person):
MARLENE ASSIE (IPNO), L. Pollacco (SPhN Saclay), W. Catford (Surrey).

Address of the CONTACT person: IPN Orsay 15 rue Georges Clémenceau, 91406 ORSAY cedex

Phone:+33 1 69 15 79 18	Fax:+33 1 69 15 64 70	E mail: assie@ipno.in2p3.fr

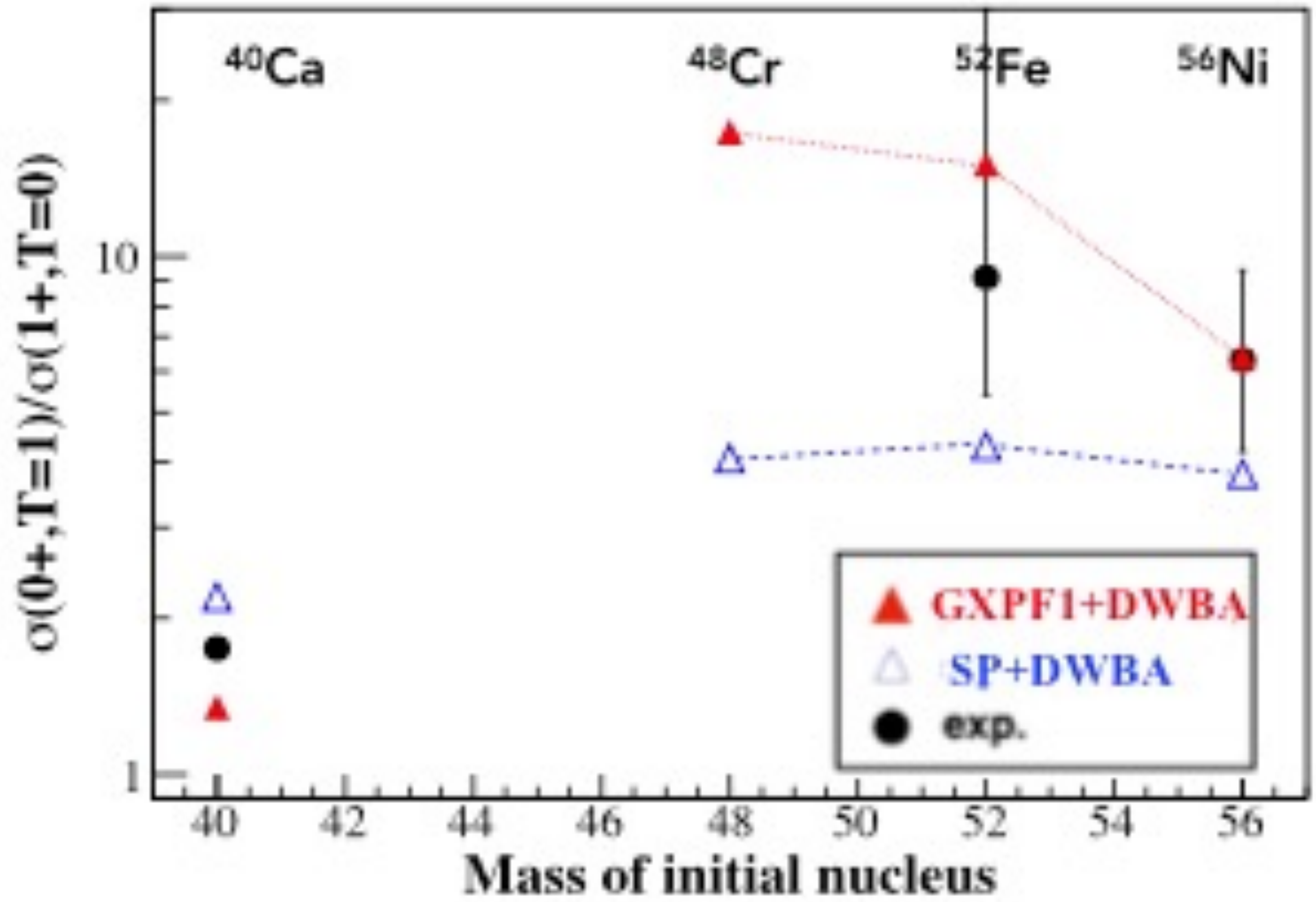
Address of the backup person:

Phone:	Fax:	E mail:

Please indicate here other participants with their affiliation (laboratory, university …)
D. Beaumel, Y. Blumenfeld, F. Hammache, N. de Séréville, S. Franchoo, E. Khan, J.A. Scarpaci, L. Lefrebvre, M. Vandebrouck, P. Morfouace, A. Matta, D. Suzuki with theoretical support from N.V. Giai, J. Margueron, P. Schuck, M. Grasso (IPN Orsay)
N. Alamanos, A. Drouart, A. Gillibert, A. Obertelli, A. Corsi, V. Lapoux, L. Nalpas, C. Simenel, Ch. Theisen (SPhN Saclay)
G. De France, P. van Isacker, F. de Oliveira, C. Stodel, B. Bastin, L. Caceres, O. Kamalou, J-C Thomas (GANIL)
R. Lemmon (Daresbury); M. Chartier (Liverpool) M. Labiche, R. Chapman (Paisley)
L. Corradi, G. deAngelis (Legnaro); W. von Oertzen (HMI Berlin)
N. Keeley (Poland); B. Fernandez-Dominguez (Spain)

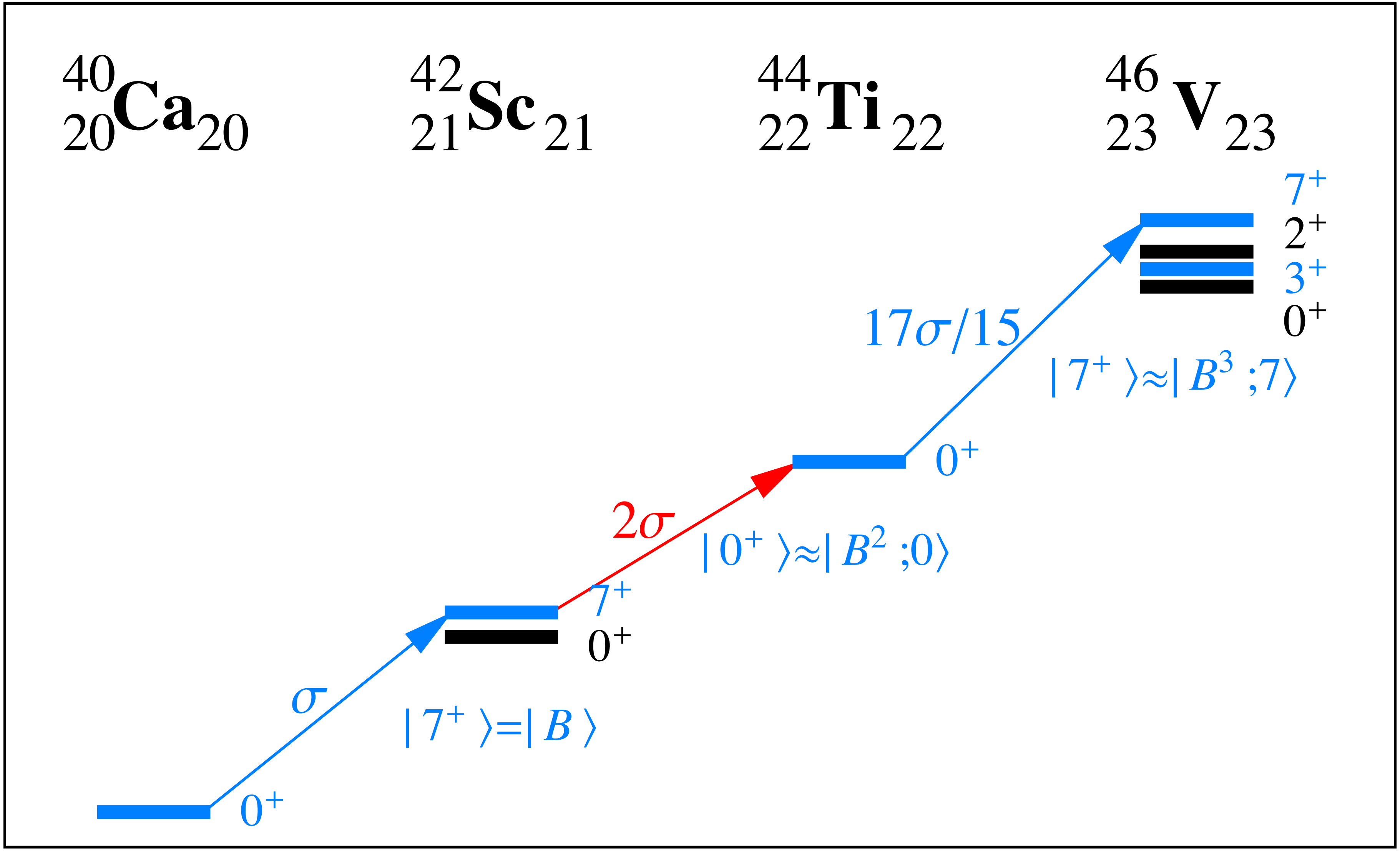
Short abstract: We propose to investigate neutron-proton pairing in the f7/2 shell through the measurement of ^{48}Cr(d,alpha), ^{48}Cr(d,^{3}He), ^{56}Ni(d,alpha) and ^{56}Ni(d,^{3}He) at 30 A. MeV. The beam is produced by fragmentation and selected with the LISE spectrometer. The experimental set-up will consist of MUST2, BTD, TIARA and 4 EXOGAM clovers.

(d,^{4}He) and (p,^{3}He) in $f_{7/2}$ shell

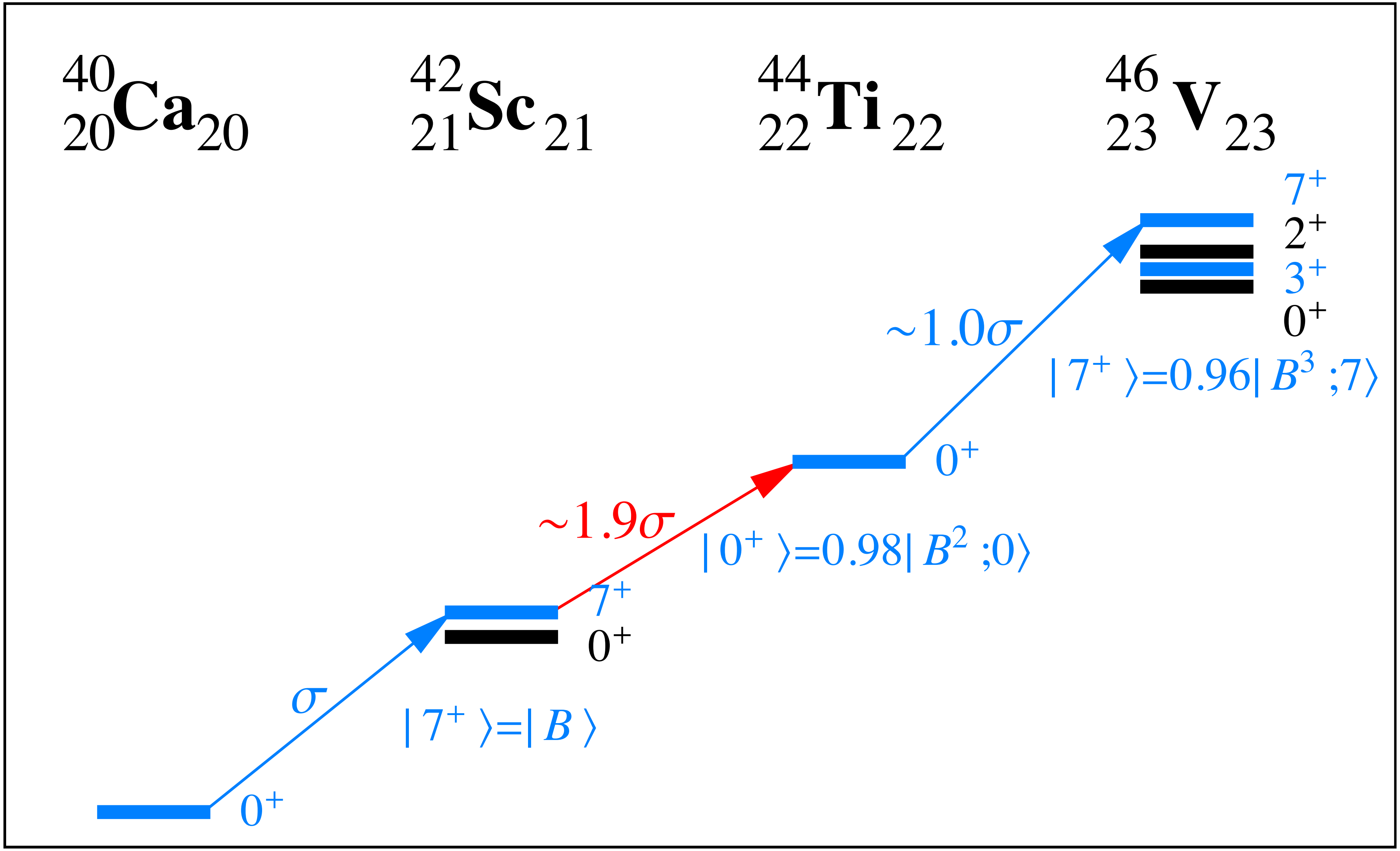


B. Le Crom *et al.*, Phys Lett. B **829** (2022) 137057

T=0 aligned pairs in Ca-Sc-Ti-V?



T=0 aligned pairs in Ca-Sc-Ti-V?



(d,^{4}He) transfer

What is the role of the spin-aligned neutron-proton pairs in the *fp*-shell ?

Study of the reactions ^{52}Fe(d,^{4}He) and ^{56}Ni(d,^{4}He)

[1]M. Assié, [2]G. de France, [3]G. de Angelis, [1]D. Beaumel, [1]Y. Blumenfeld, [2]E. Clément, [4]B. Fernandez-Dominguez, [3]F. Galtarossa, [1]V. Girard-Alcindor, [3]A. Gottardo, [1]F. Hammache, [1]H. Jacob, [5]N. Keeley, [4]A.O. Macchiavelli, [3]D. Mengoni, [1]O. Nasr, [1]N. de Séréville, [1]I. Stefan,[2]T. Roger, [7]F. Rotaru, [7]M. Stanoiu, [2]O. Sorlin, [2]J-C. Thomas, [2]P. van Isacker

[1] *IJCLab Orsay,[2]GANIL, [3]LNL, INFN-University of Padova, [4] University of Santiago di Compostela, [5]National centre for nuclear physics, Warsaw, [6]ORNL, [7]NIPNE Romania*

What is the question?

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- *Do* $T = 0$ *pairing correlations exist?*

The Osaka experiments

Proton inelastic scattering at E_p=295 MeV on *sd*-shell nuclei.

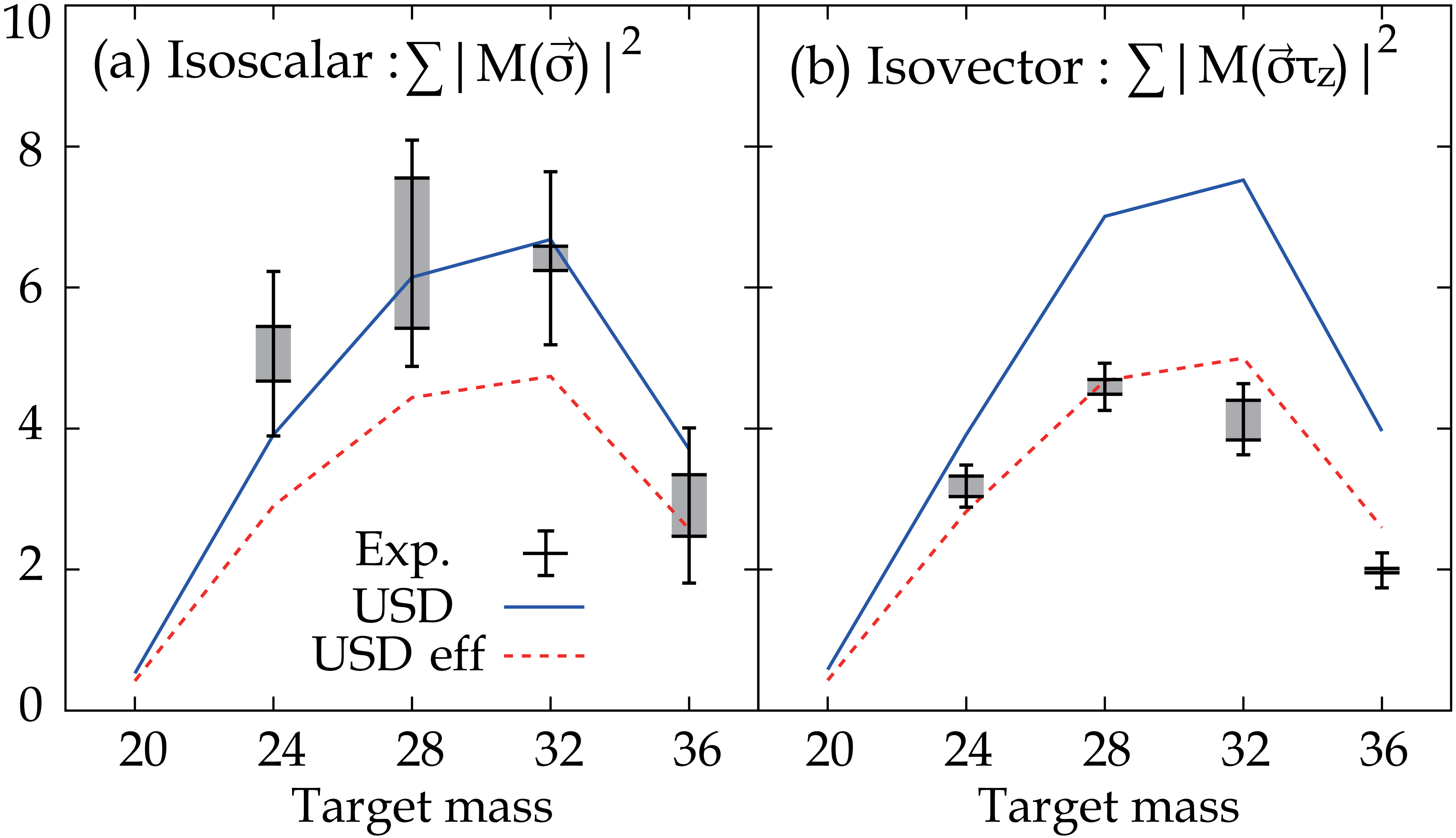
Isoscalar and isovector spin-M1 transition strengths up to E_x=16 MeV.

$$S(\boldsymbol{\sigma}) = \sum_f \langle 1_f^+ || \Sigma_k \boldsymbol{\sigma}_k || 0_1^+ \rangle^2$$

$$S(\boldsymbol{\sigma}\tau_z) = \sum_f \langle 1_f^+ || \Sigma_k \boldsymbol{\sigma}_k \tau_{z,k} || 0_1^+ \rangle^2$$

H. Matsubara *et al.,* Phys. Rev. Lett. **115** (2015) 102501

The experimental result



H. Matsubara *et al.*, Phys. Rev. Lett. **115** (2015) 102501
H. Sagawa, T. Suzuki, Phys. Rev. C **97** (2018) 054333

Spin-spin correlations $\langle \boldsymbol{S}_n \cdot \boldsymbol{S}_p \rangle$

Neutron and proton spin operators

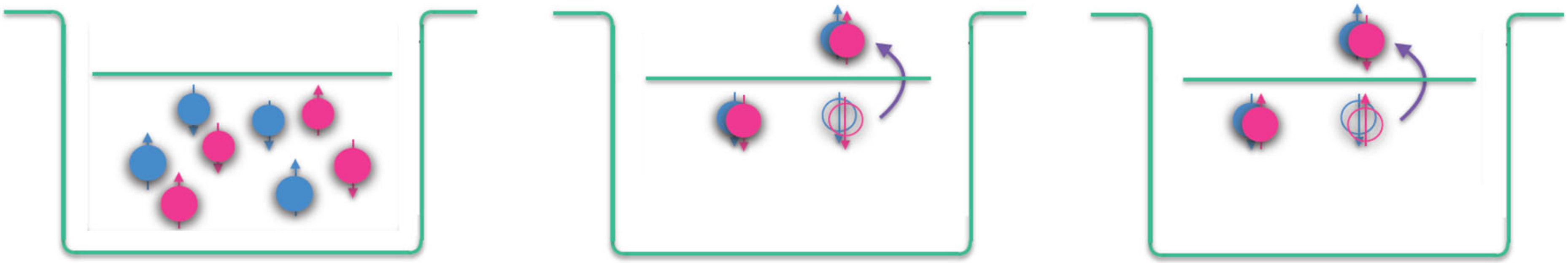
$$\boldsymbol{S}_n = \sum_{k \in n} \boldsymbol{\sigma}_k , \qquad \boldsymbol{S}_p = \sum_{k \in p} \boldsymbol{\sigma}_k$$

Relation between M1 transitions and neutron-proton spin-spin correlations:

$$\langle 0_1^+ | \boldsymbol{S}_n \cdot \boldsymbol{S}_p | 0_1^+ \rangle \approx \frac{1}{16} \{ S(\boldsymbol{\sigma}) - S(\boldsymbol{\sigma} \tau_z) \}$$

$\langle \boldsymbol{S}_n \cdot \boldsymbol{S}_p \rangle$: a pairing probe

$$\left\langle \vec{s}_n \cdot \vec{s}_p \right\rangle = \begin{cases} +\dfrac{1}{4} & \text{for IS } np \text{ pair (deuteron)} \\ & \quad \text{statistical weight} = 3 \\ -\dfrac{3}{4} & \text{for IV } np \text{ pair} \\ & \quad \text{statistical weight} = 1 \end{cases}$$



IS np pairing

IV np pairing

$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle = 0$

$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle > 0$

$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle < 0$

Unperturbed ground state

Correlated ground state

$\langle \boldsymbol{S}_n \cdot \boldsymbol{S}_p \rangle$: a pairing probe

Some simple results:

LS-coupling

$$\left\langle \left(l_n,\tfrac{1}{2}\right)\left(l_p,\tfrac{1}{2}\right);LS\middle|S_n\cdot S_p\middle|\left(l_n,\tfrac{1}{2}\right)\left(l_p,\tfrac{1}{2}\right);LS\right\rangle =$$

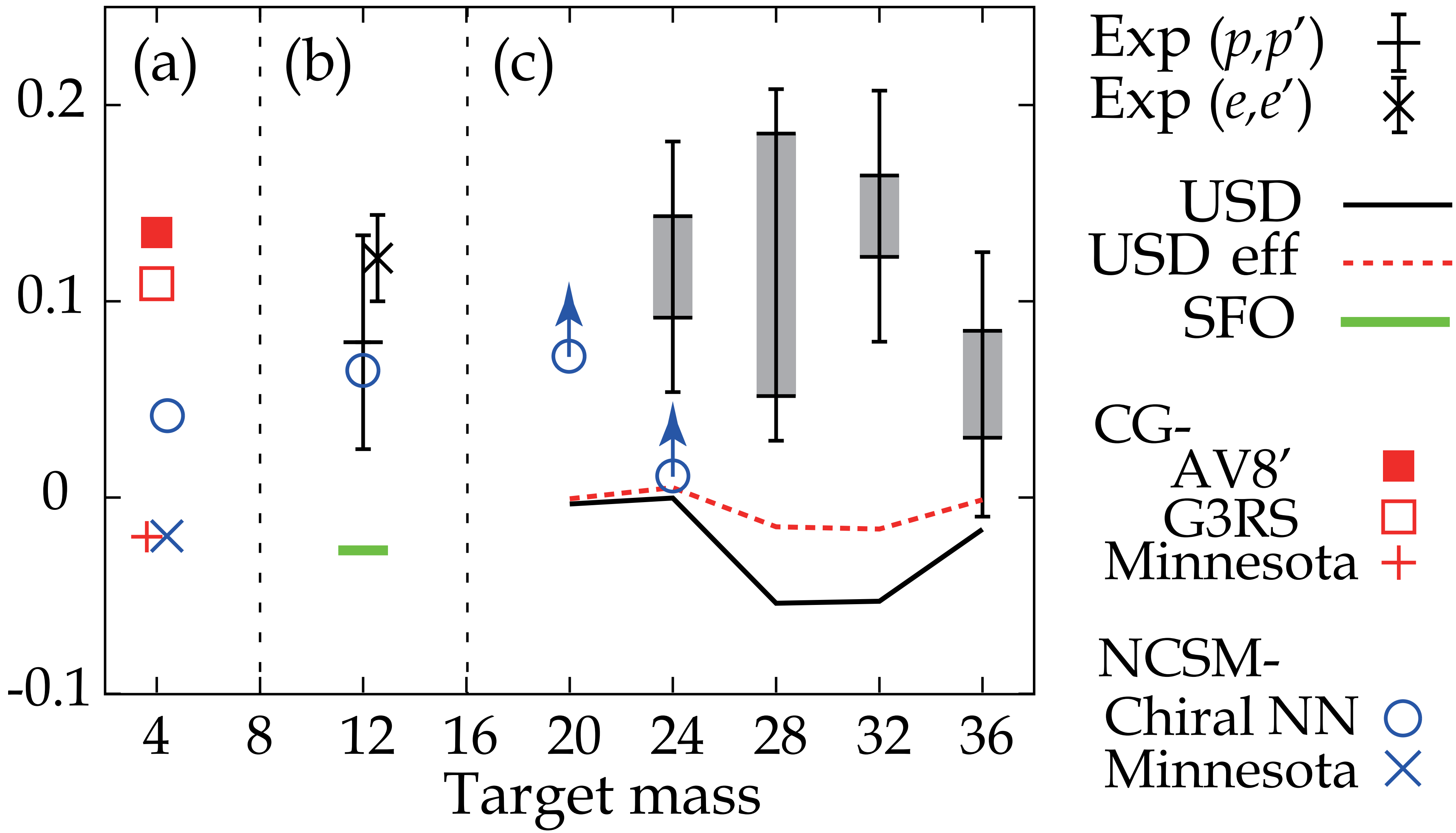
$$= \frac{2}{3}(-)^{S+1}\begin{Bmatrix} \frac{1}{2} & \frac{1}{2} & 1 \\ \frac{1}{2} & \frac{1}{2} & S \end{Bmatrix} = \begin{cases} +\frac{1}{4}, & S=1, T=0 \\ -\frac{3}{4}, & S=0, T=1 \end{cases}$$

jj-coupling:

$$\left\langle j_n j_p; J\middle|S_n\cdot S_p\middle|j_n j_p; J\right\rangle = \frac{J(J+1)-2j(j+1)}{2(2l+1)^2}$$

P. Van Isacker, A.O. Macchiavelli, Eur. J. Phys. **57** (2021) 178

Spin-spin correlations $\langle \boldsymbol{S}_n \cdot \boldsymbol{S}_p \rangle$



Schematic shell-model calculations

Single-l shell (with $j = l \pm \frac{1}{2}$) and a SDI with isoscalar and isovector strengths:

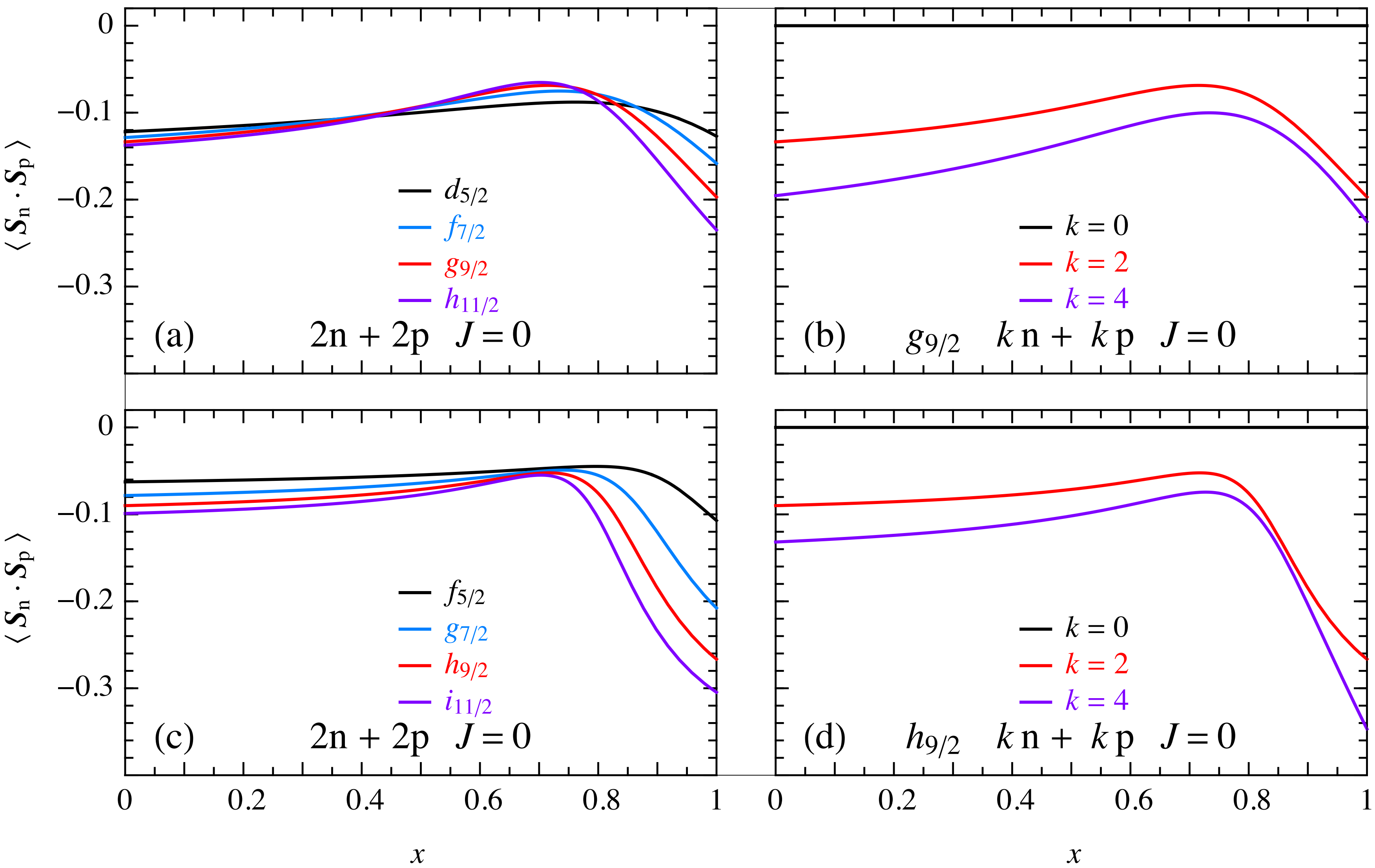
$$\hat{H} = \sum_{\pm} \varepsilon_{\pm} \hat{n}_{\pm} - \sum_{T=0,1} a_T \sum_{i<j} \delta(\boldsymbol{r}_i - \boldsymbol{r}_j)\, \delta(\boldsymbol{r}_i - \boldsymbol{R}_0)$$

Spin-spin correlation $\langle \boldsymbol{S}_n \cdot \boldsymbol{S}_p \rangle$ is always negative in the ground state of even-even nuclei!

$$x = \frac{a_0}{a_0 + a_1}, \qquad y = \frac{\Delta\varepsilon/(a_0 + a_1)}{5 + |\Delta\varepsilon/(a_0 + a_1)|}$$

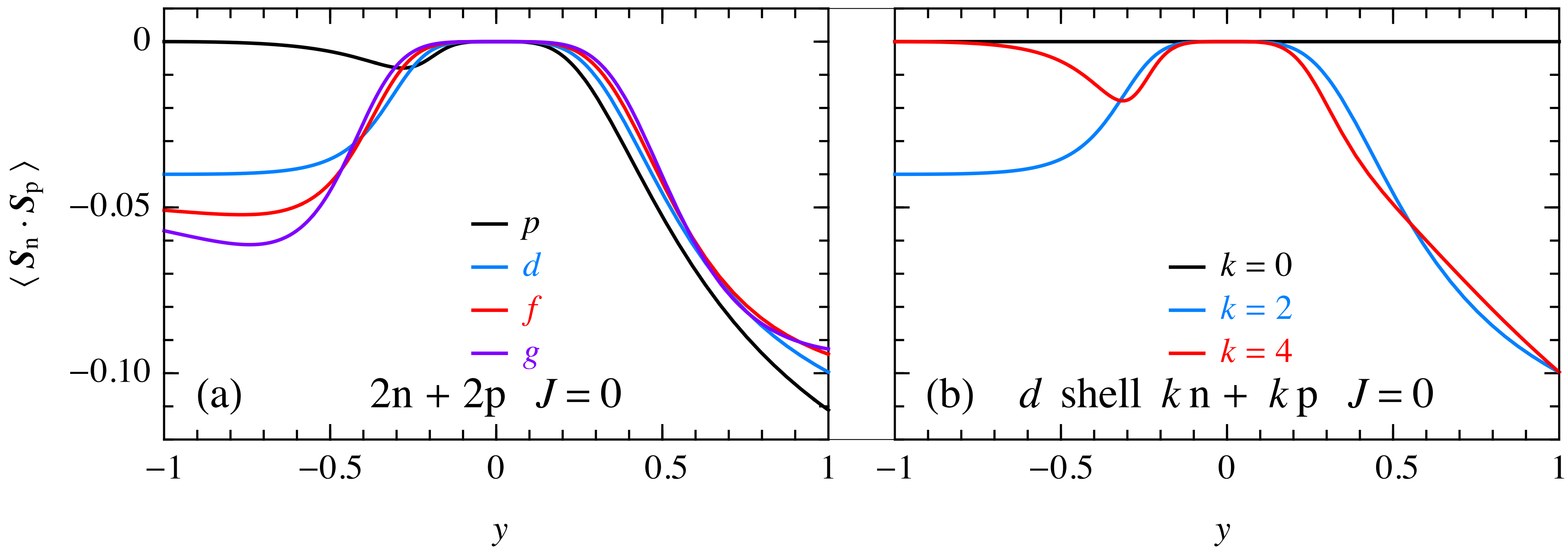
P. Van Isacker, A.O. Macchiavelli, Eur. J. Phys. **57** (2021) 178

Examples



0
−0.1
−0.2
−0.3
$\langle S_n \cdot S_p \rangle$
$d_{5/2}$
$f_{7/2}$
$g_{9/2}$
$h_{11/2}$
(a) 2n + 2p $J = 0$
$k = 0$
$k = 2$
$k = 4$
(b) $g_{9/2}$ k n + k p $J = 0$
$f_{5/2}$
$g_{7/2}$
$h_{9/2}$
$i_{11/2}$
(c) 2n + 2p $J = 0$
(d) $h_{9/2}$ k n + k p $J = 0$
0 0.2 0.4 0.6 0.8 1
x

Examples



0
−0.05
−0.10
$\langle S_n \cdot S_p \rangle$
p
d
f
g
(a) 2n + 2p J = 0
k = 0
k = 2
k = 4
(b) d shell k n + k p J = 0
−1
−0.5
0
0.5
1
y
y

(p,p') and (d,d') on $^{44,46}Ti$

Research Proposal
PHYSICAL SCIENCES, SSC FACILITY
iThemba Laboratory for Accelerator Based Sciences

1 Title of Proposed Experiment

Ground state neutron-proton spin-spin correlations studied by (p,p') and (d,d') scattering

2 Date

August 16th, 2019

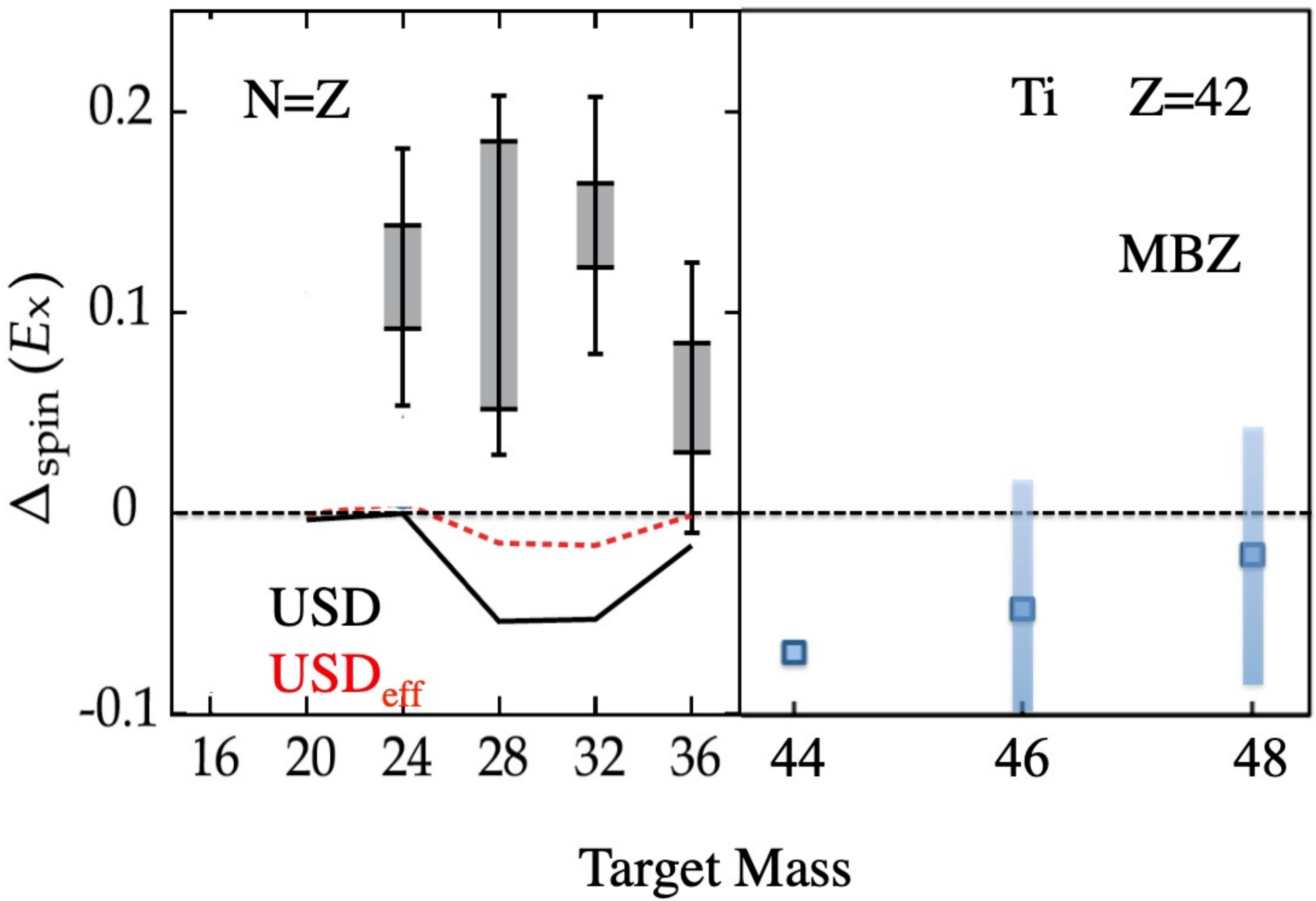
3 Members of the Collaboration

Spokesperson: A. O. Macchiavelli[a1]

H. L. Crawford [a], C. M. Campbell[a], R. M. Clark[a], M. Cromaz[a], P. Fallon[a], I. Y. Lee[a], C. Morse[a], C. Santamaria[a], L. Pellegri[b,c], R. Neveling[c], M. Wiedeking[c], P. Adsley[c,b], L. M. Donaldson [c], R. V. F. Janssens[d], H. Matsubara[e], P. von Neumann-Cosel[f], F.D. Smit[c], and A. Tamii[g]

Theoretical support: P. Van Isacker[h]

(p,p′) and (d,d′) on ^{44,46}Ti



Conclusion

Isoscalar (isovector) spin-M1 transitions are (not) quenched.

This observation has no simple explanation in the shell model.

Outlook

Experiments:

Investigate odd-odd N=Z nuclei;

Go slightly off N=Z line.

Theory:

More realistic Hamiltonian (shell mixing, tensor force,...)

Revisit isoscalar pairing?

High-momentum correlated nucleon pairs?