Nuclear Physics Mid Term Plan in Italy

LNL – Session

Legnaro, April 11^{th}-12^{th} 2022

Nuclear Physics
Mid Term Plan in Italy

N~Z and isospin symmetry

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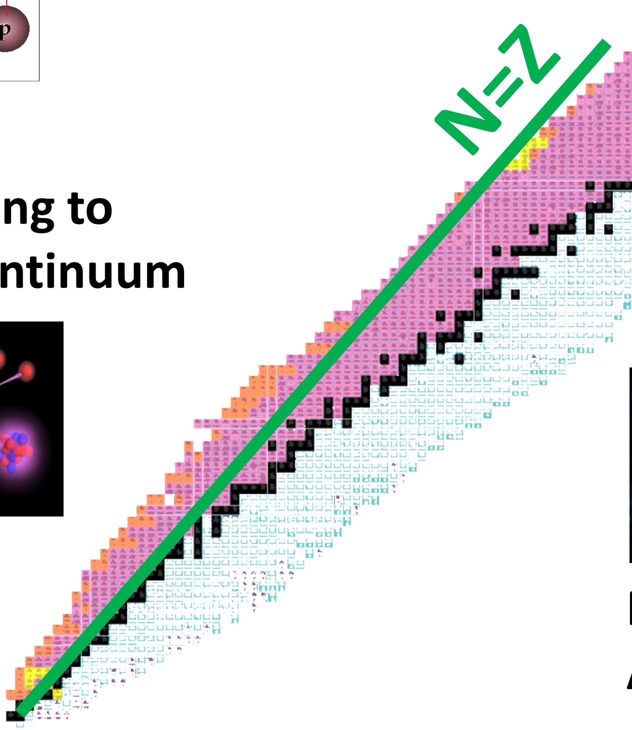
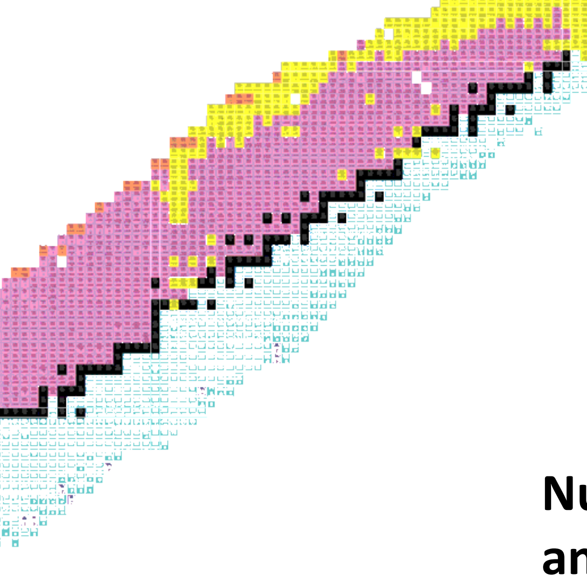
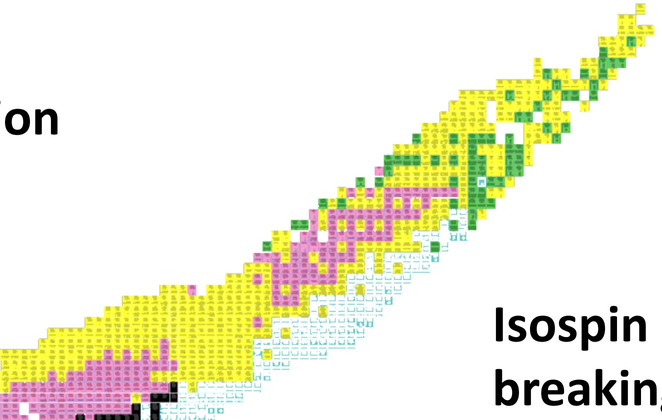
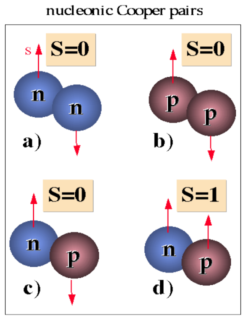
The N=Z richness



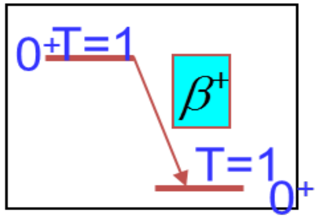




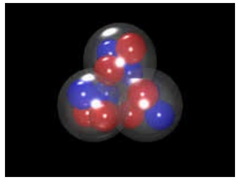
p-n pairing



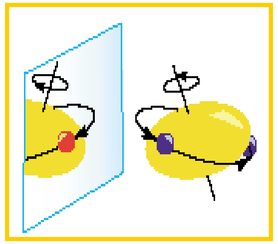
fundamental interactions



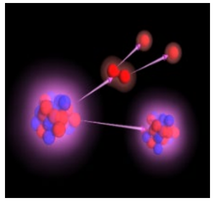
alpha clusterization



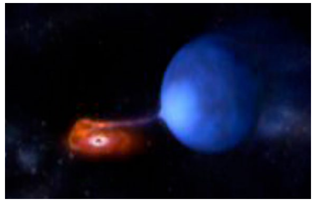
Isospin symmetry breaking



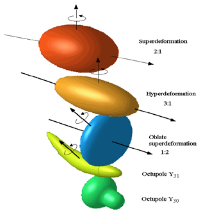
Coupling to the continuum

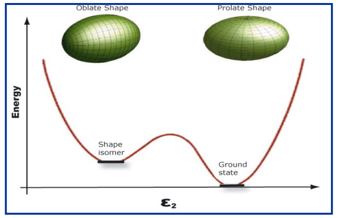


Nuclear Astrophysics



Nuclear shapes and coexistence





Open problems in nuclear structure of N~Z nuclei

Understanding the nuclear interaction

Some properties of the nuclear interaction are unique or enhanced in N~Z nuclei

- Quadrupole+ Pairing interplay
  - Quadrupole → deformation
  - Pairing → Role of p-n T=0 pairing
- Isospin symmetry (breaking)
- Fundamental interactions

Working group:
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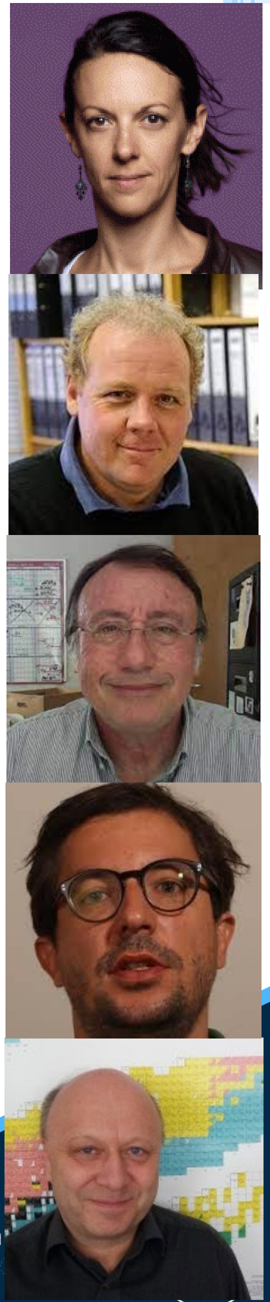
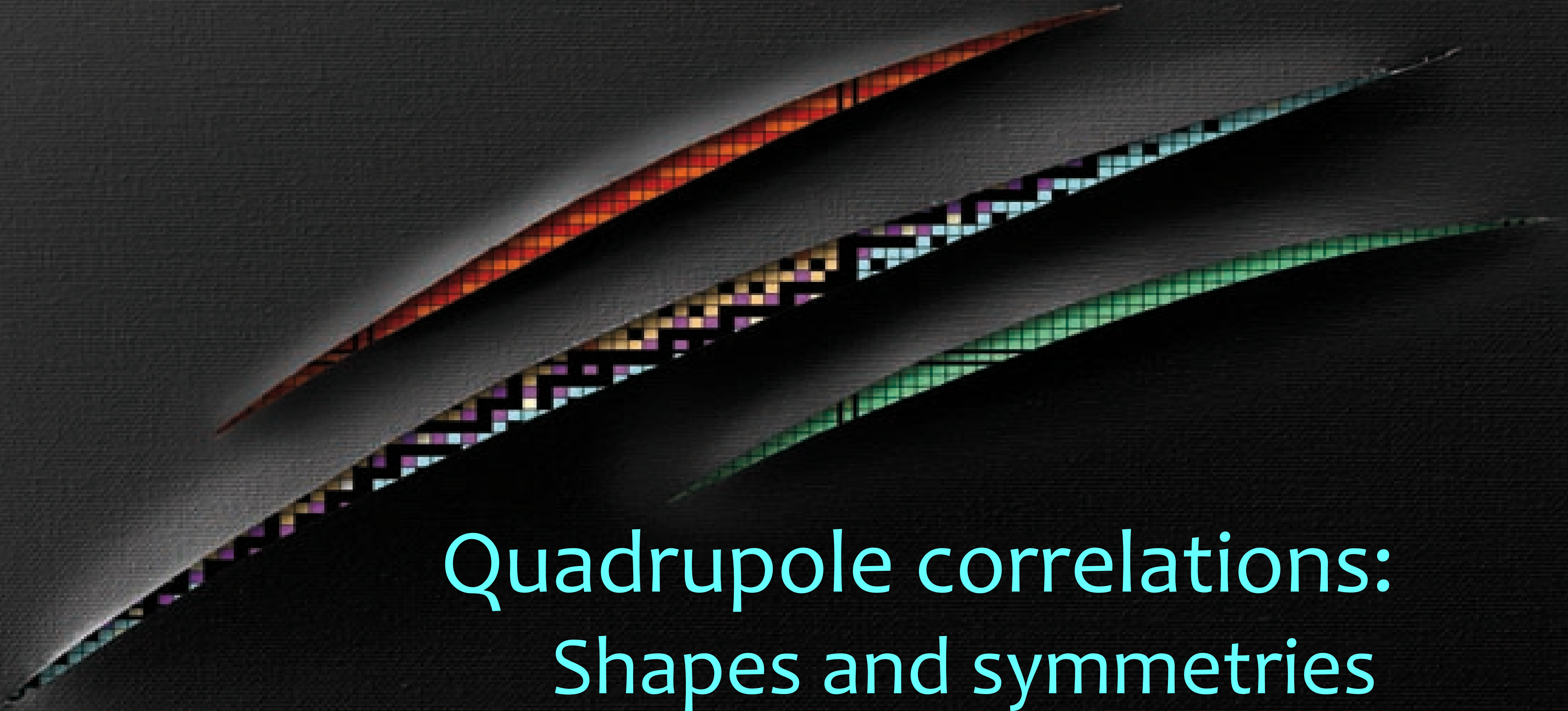
Augusto Macchiavelli (Oak Ridge)
Francesco Recchia (Padova)
Dirk Rudolph (Lund)
Silvia Lenzi (Padova)

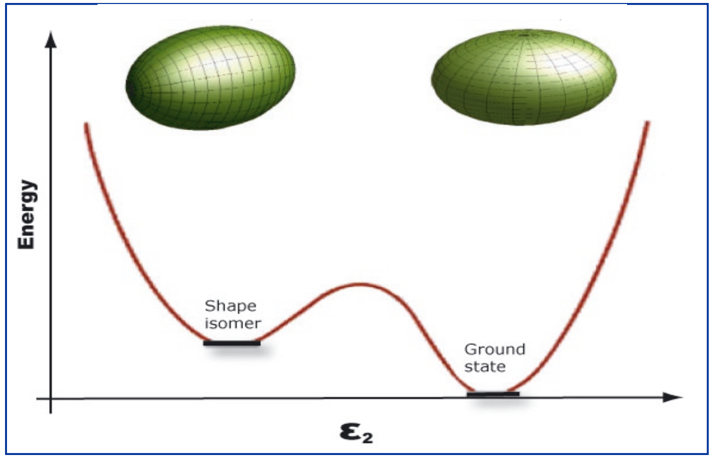




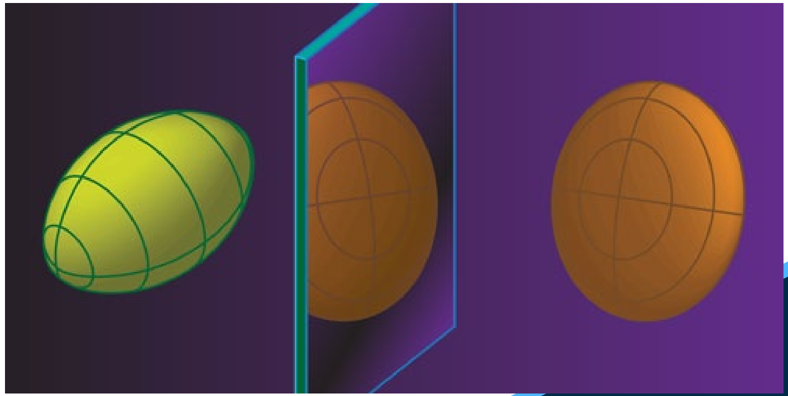
Quadrupole correlations:
Shapes and symmetries

Quadruopole collectivity in N=Z nuclei

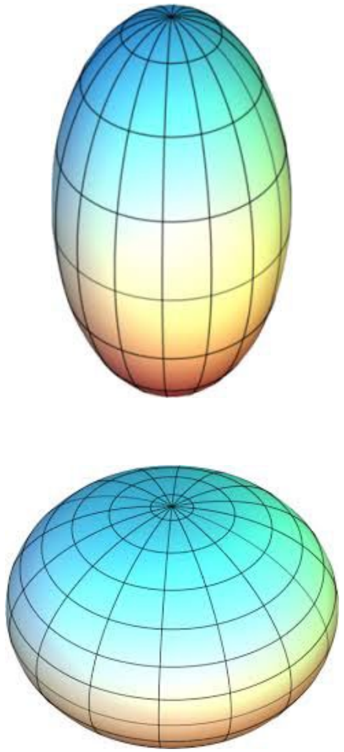
Along the N=Z line quadrupole correlations are quite strong and in most of the cases govern the nuclear structure properties.
This gives rise to different nuclear shapes and their coexistence.



The development of nuclear deformation is a key property central to our understanding of the nuclear force.



Quadrupole deformation: a simple model



The spherical nuclear field is close to the harmonic oscillator potential.

In the limit of degeneracy of the single-particle energies of a major harmonic oscillator shell, and in the presence of an attractive Q.Q proton-neutron interaction, the ground state of the many-body nuclear system is maximally deformed.

Elliott SU(3) in the sd shell

So, at low energy, nuclear states tend to maximize the intrinsic quadrupole moment

Quadrupole moment in N=Z nuclei

The nuclear quadrupole moment is the sum of the single-particle quadrupole moments

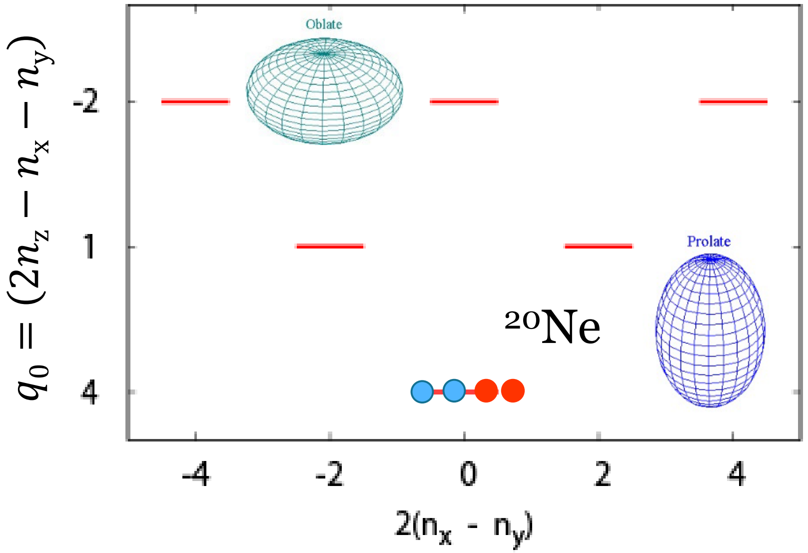
$$q_{sp} = (2n_z - n_x - n_y)$$

where the principal quantum number $N = (n_x + n_y + n_z)$

In the *sd* shell $N = 2$
$N = n_x + n_y + n_z = 2$
there are 3 possible values:

$$q_{sp} = 4, 1, -2$$

The “intrinsic orbits” in SU3



We obtain the nuclear quadrupole moment by filling these fourfold (2p + 2n) degenerate “orbits” along the N=Z line

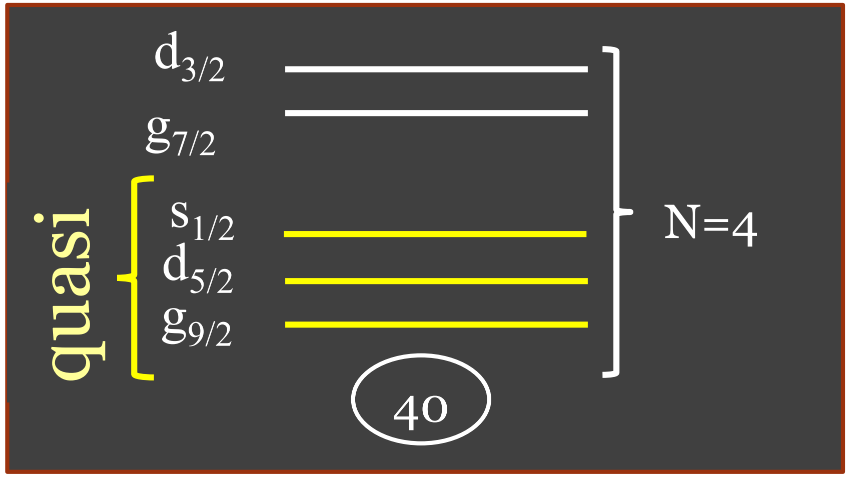
- start filling from below → prolate deformation
- start filling from above → oblate deformation

SU3 approximate symmetries

Elliott's SU3 works well in the *sd* shell but fails for upper shells where the spin-orbit interaction introduces large energy shifts

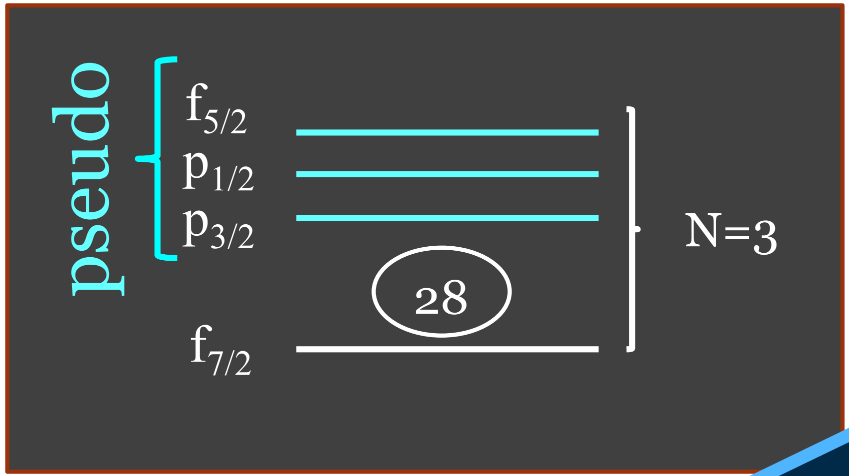
Quasi SU3

applies to the lowest $\Delta j = 2$, $\Delta \ell = 2$ orbits in a major HO shell



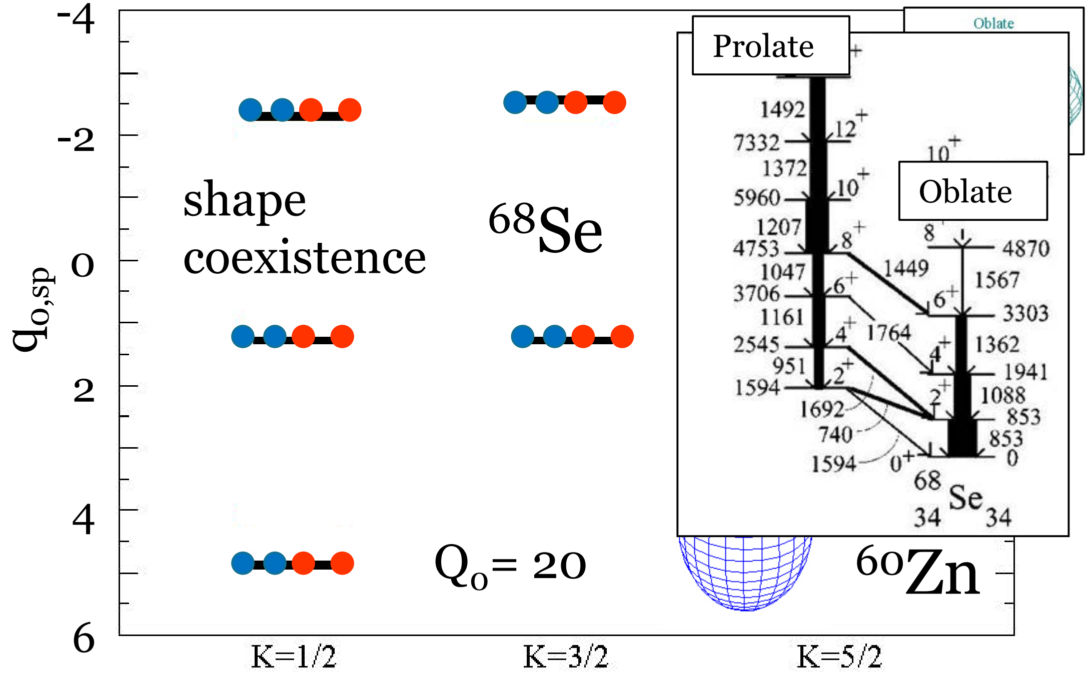
Pseudo SU3

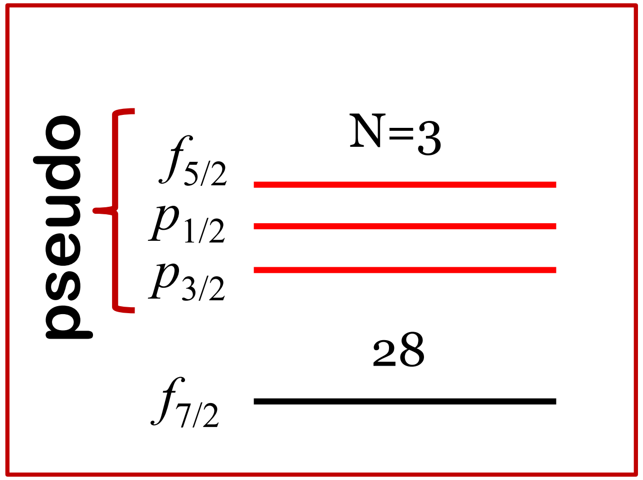
applies to a HO space where the largest *j* orbit has been removed.



A.P. Zuker et al., PRC 92, 024320 (2015)

Quadrupole moment in Pseudo SU3 space



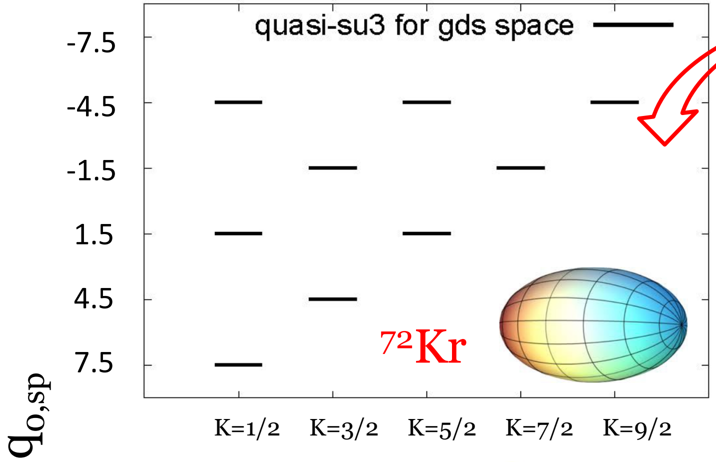


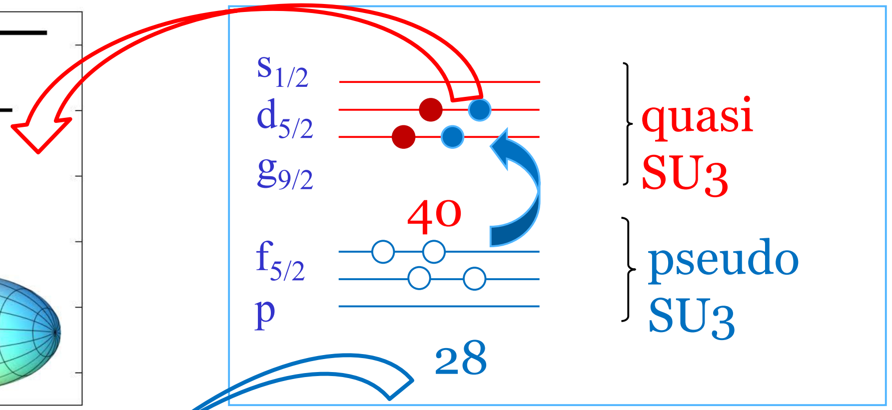
We obtain Q_0 by summing those
of the single particles/holes in each “orbit”

A.P. Zuker et al., PRC 92, 024320 (2015)

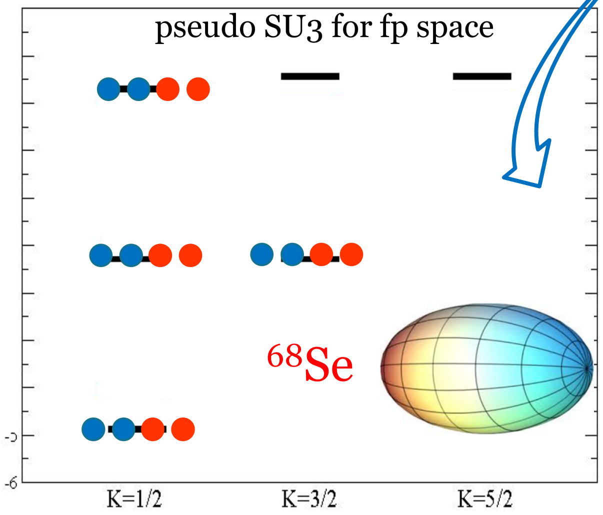
Quadrupole moment in Pseudo+Quasi SU3 tandem

quasi





pseudo



Particle-hole excitations in the pseudo + quasi space maximize the quadrupole moment.

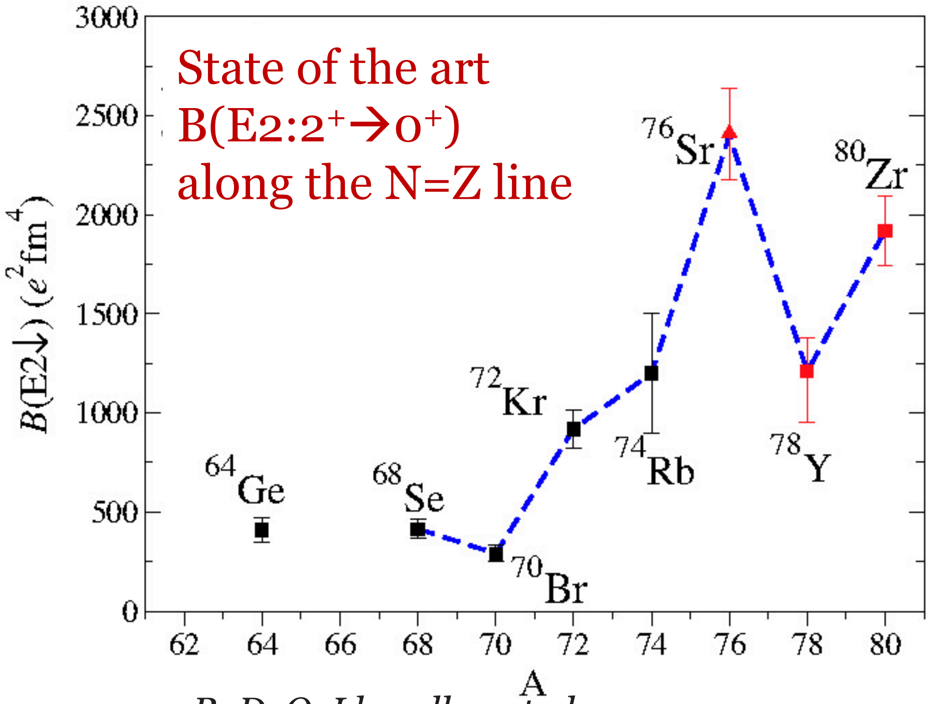
The quadrupole correlation energy results much larger than the energy cost to promote the particles

Based on these dynamical symmetries we can predict different shapes in N=Z nuclei

A.P. Zuker et al., PRC 92, 024320 (2015)

Shapes and shape coexistence in N=Z at LNL

A way to test the degree of deformation is to measure the B(E2) of excited states



R. D. O. Llewellyn et al., Phys. Rev. Lett. 124, 152501 (2020)

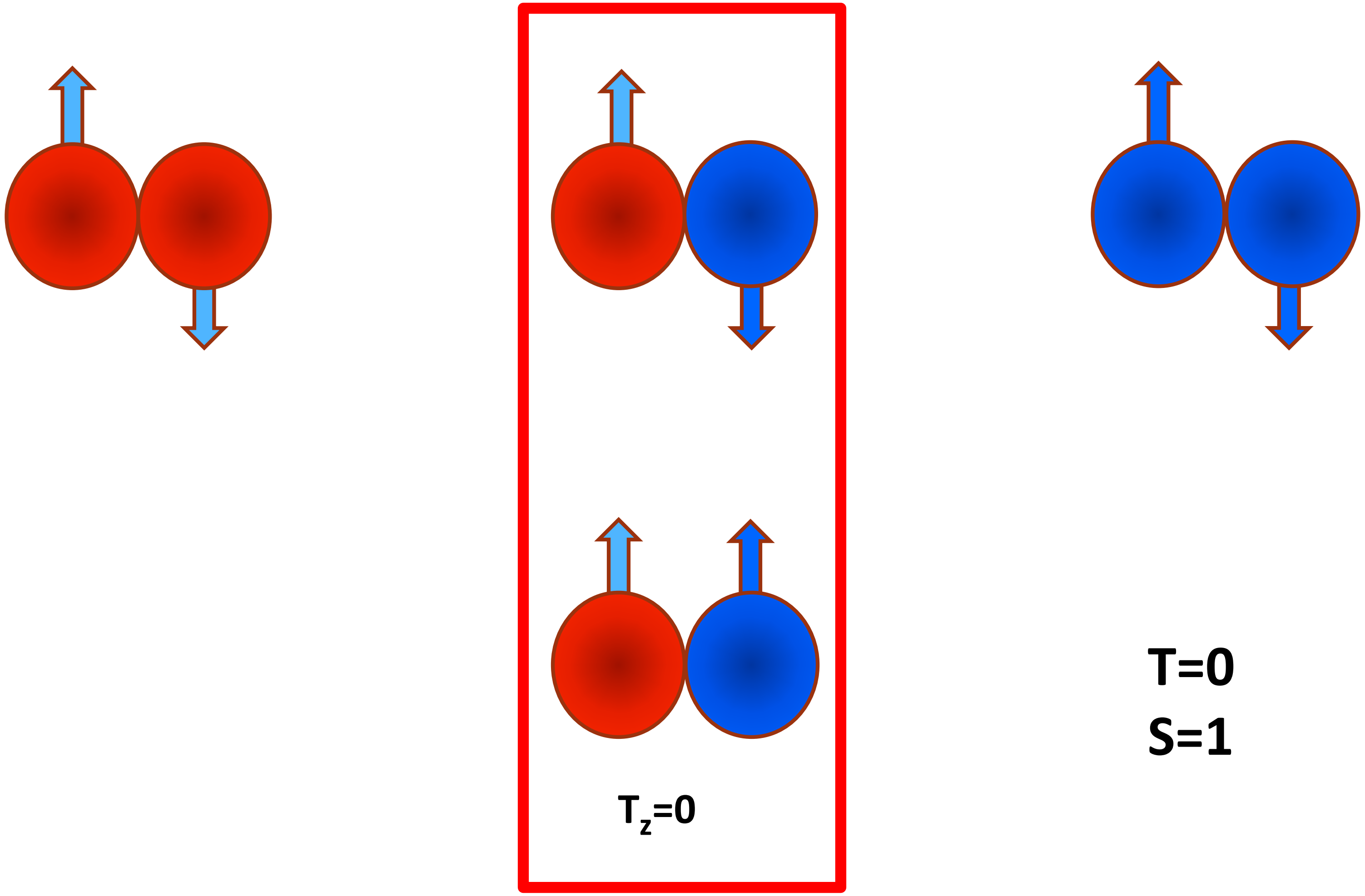
With the exception of ^{72}Kr, in N=Z nuclei with A>64 only the B(E2: $2^+ \rightarrow 0^+$) has been measured so far.

Shape coexistence is predicted in most of N=Z nuclei.

Lifetimes of excited states in N~Z nuclei can be measured using stable beams in fusion-evaporation and multinucleon transfer reactions
→ combining AGATA + NEDA + charged-particle det. + (Plunger)
or AGATA+ PRISMA + differential plunger

Pairing: the role of T=0 pn

Pairing interaction



T=1
S=0

Isovector Pairing

T=0
S=1

Isoscalar Pairing

Role of T=0 pn pairing

Does isoscalar pairing give rise to collective modes?

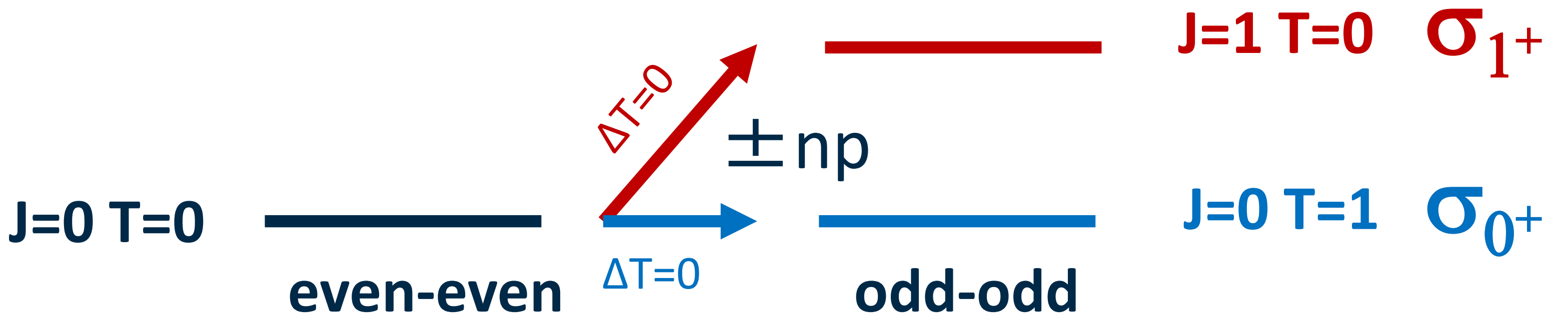
Possible signatures:

- Binding energy differences
- Low-lying states of odd-odd self-conjugate nuclei
- Rotational properties: moments of inertia, alignments
- Beta decay
- DIRECT REACTIONS

Pure np transfer

(p, ^{3}He), (^{3}He,p)	ΔT=0,1
(d,α), (α,d)	ΔT=0
(α, ^{6}Li), (^{6}Li,α)	ΔT=0

+ (^{3}He,p)
- (p, ^{3}He)



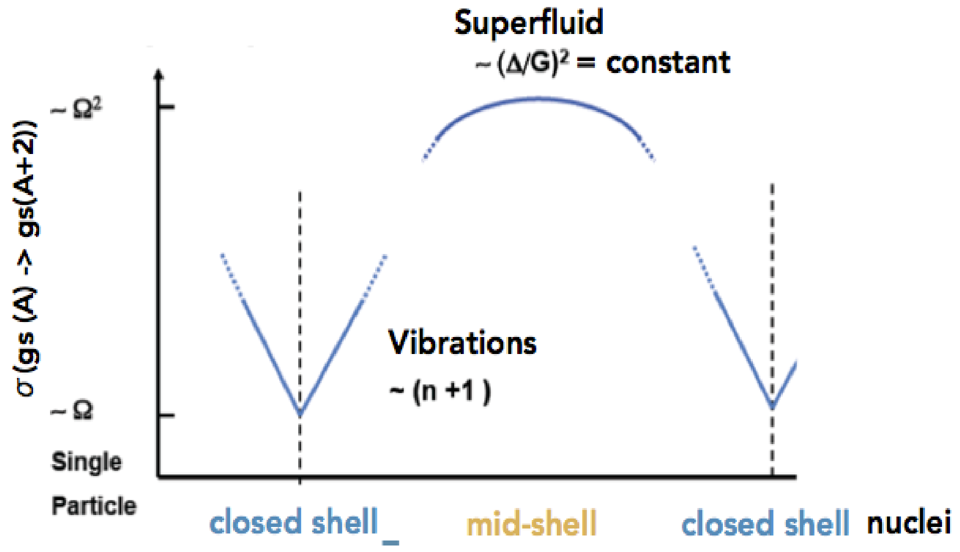
(^{3}He,p) L=0 transfer – forward peaked

Measure the *np* transfer cross sections to T=1 and T=0 states

Both absolute σ(J=0) and σ(J=1) <u>and</u> relative σ(J=0) / σ(J=1) tell us about the character and strength of the pn correlations

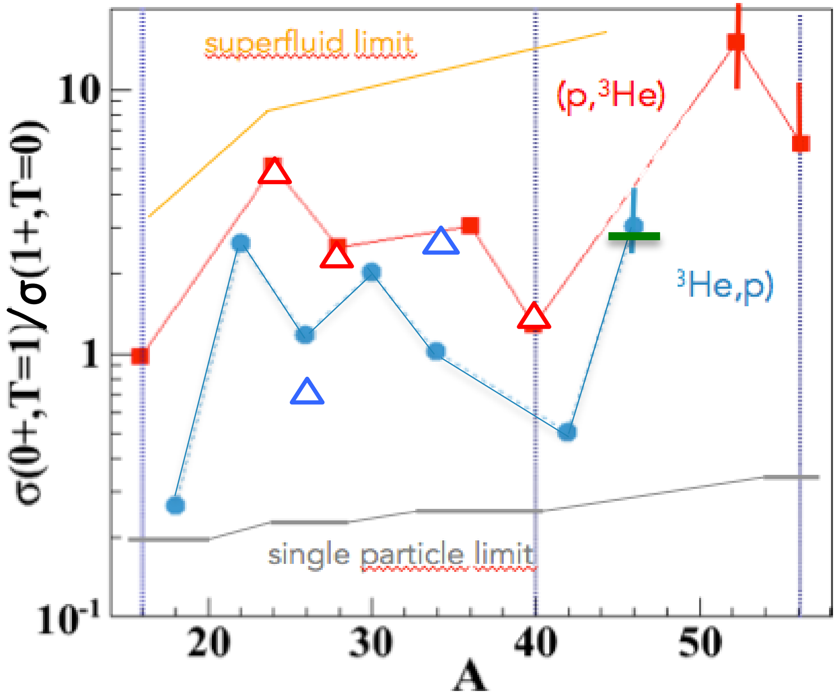
T=0 vs T=1 pn transfer

T=1 2n transfer



From 2n transfer the T=1 cross section, as a function of N, shows a parabolic behaviour along a shell of degeneracy Ω with the superfluid regime at a plateau in the middle of the shell

compilation of T=0/T=1 pn transfer



Y. Ayyad et al., PRC96 (2017)

Warning!

- Ratios obtained in different experiments and at different energies --> effect of the reaction mechanism
- L=0 and L=2 contributions overlaping

--> angular distributions needed

Short and Mid-term opportunities at LNL

^{36}Ar(p,^{3}He) and (^{3}He,p)

complete systematics on the *sd* shell

^{46}V, ^{50}Mn(p,^{3}He) and (^{3}He,p)

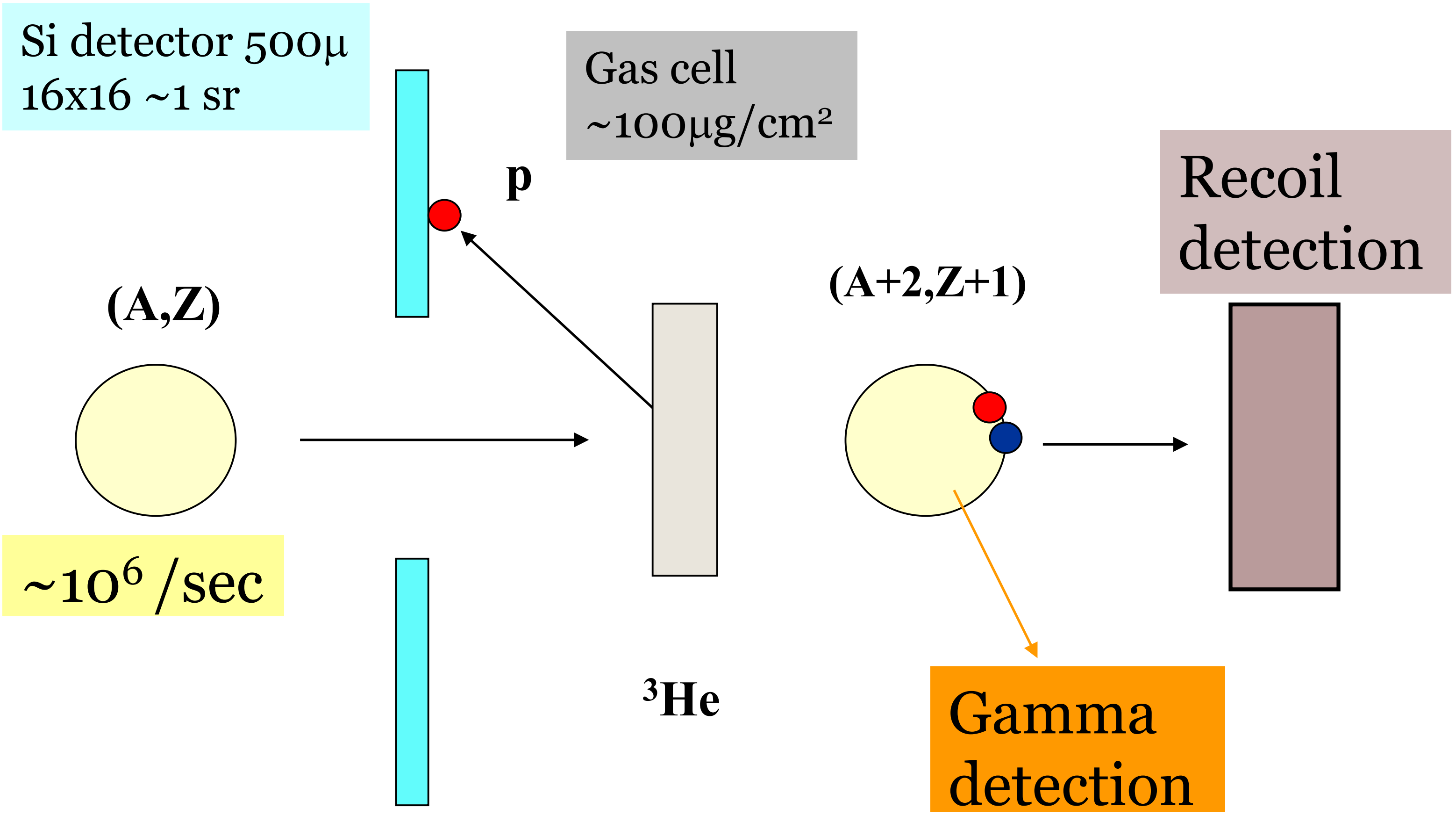
complementary studies from odd-odd T=1 ground states to T=0,1 final states in even-even

^{46}V, ^{50}Mn(d,α) and (α,d); (α,^{6}Li) and (^{6}Li,α)

complementary studies to the reactions above

SPES exotic beams for science

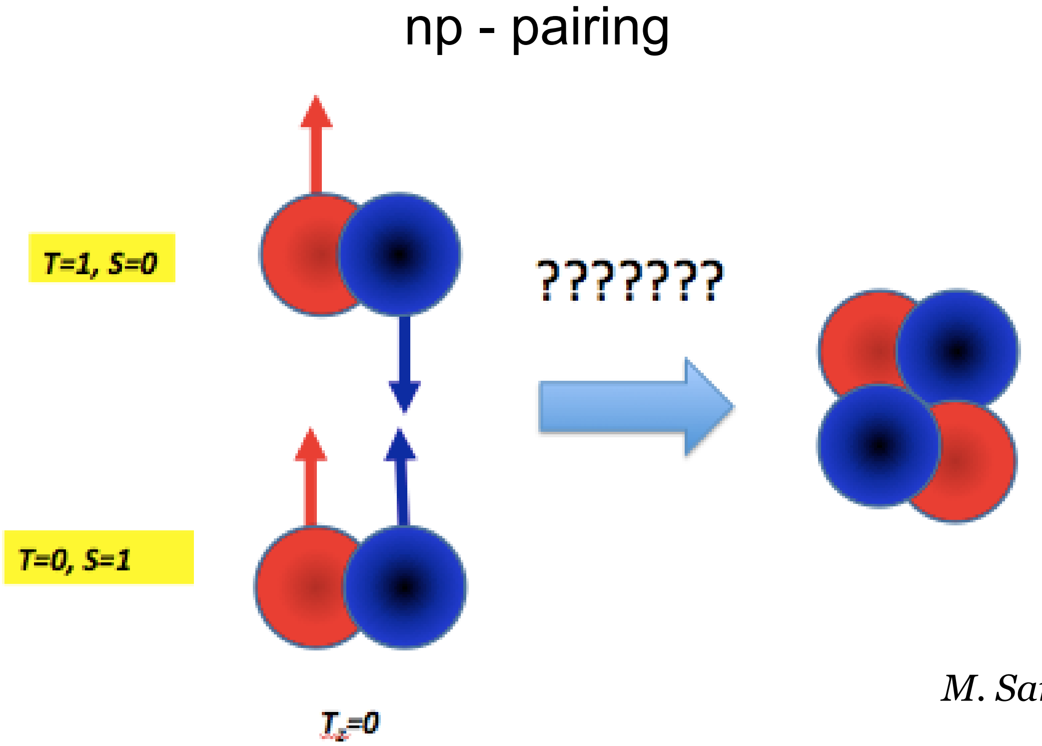
Possible experimental setup



Measure E(Θ), dσ/dΩ (Θ), σ

~ 20
counts/day

Quartet condensate



Alpha-like quartets are predicted to appear in the ground state of alpha-conjugate nuclei as a collective state

M. Sambataro and N. Sandulescu, Eur. Phys. J. A 53, 47 (2017)

ground state of even-even N=Z nuclei are close to a phase transition between an alpha boson-condensed gas and a quantum liquid

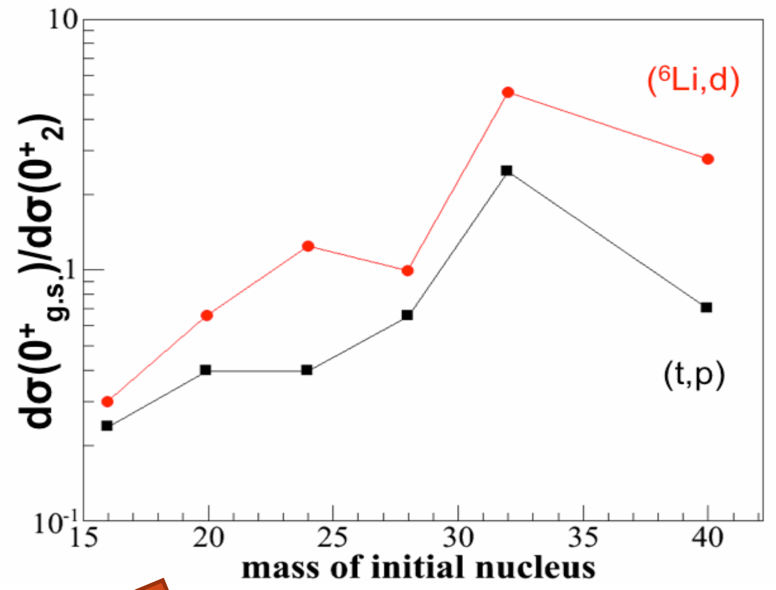
Lattice effective field theory calculations by S. Elhatisari et al, arXiv: 1602.04539 (2016); Nature 528, 111 (2015)

Short-term opportunities: Quarteting

- **test of quartet condensation** *alpha particle transfer along N=Z line*

$$< QCM(A+4) | Q^{+} | QCM(A) > \qquad | QCM > \equiv (Q^{+})^{n_q} | - >$$

$$^{16}O \xrightarrow{\alpha} {}^{20}Ne \xrightarrow{\alpha} {}^{24}Mg \xrightarrow{\alpha} {}^{28}Si \xrightarrow{\alpha} {}^{32}S$$



Revisit the *sd* shell:

$^{12}C + {}^{28}Si \rightarrow {}^{32}S + {}^{8}Be \rightarrow {}^{32}S +$ 2 alphas

(^{6}Li,d) reactions: a powerful tool due to its clusterization
(^{6}Li, ^{4}He) reaction will test also T=0 pn pairing

Data obtained with different energy regimes from 26 to 75 MeV and with different experimental setups: questionable consistency of the systematics

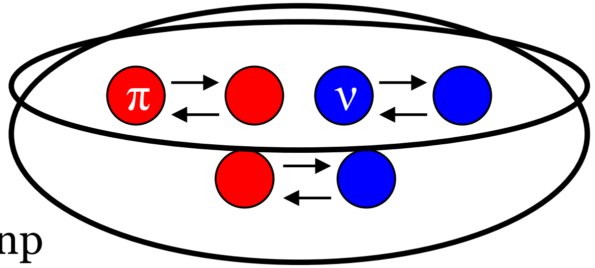
M. Sambataro and N. Sandulescu, Eur. Phys. J. A 53, 47 (2017)

Isospin symmetry (breaking)

Neutron-proton exchange symmetry

Charge Symmetry: $V_{pp}=V_{nn}$

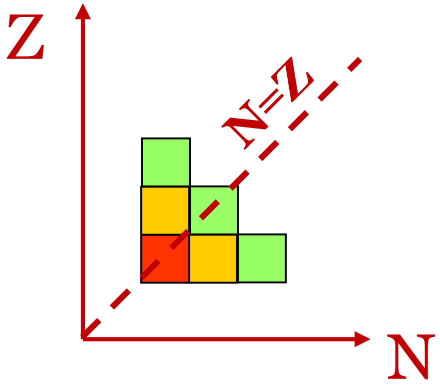
Charge Independence: $(V_{pp} + V_{nn})/2= V_{np}$

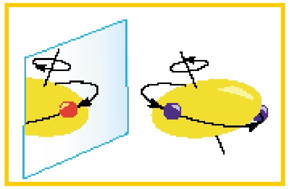


Deviations are small

The electromagnetic interaction lifts the degeneracy of the analogue states, but does not generally affect the underlying symmetry.

Energy differences between analogue states





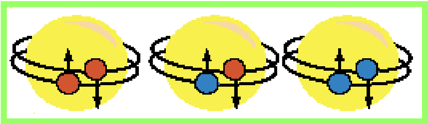
Mirror Energy Differences (MED)

$$MED_J = Ex_{J,T_z=-T} - Ex_{J,T_z=+T}$$

Test the charge symmetry of the interaction

Triplet Energy Differences (TED)

$$TED_J = Ex_{J,T_z=-T} + Ex_{J,T_z=+T} - 2Ex_{J,T_z=0}$$



Test the charge independency of the interaction

Extensive studies of these energy differences have given important information on:

- Evolution of radii (deformation) along a rotational band
- The configuration of the states
- Isospin non-conserving terms of the interaction
- Estimate the neutron skin

A mature research field that relies on the isospin purity of the states

Testing the EM transition (isospin) rules

A crucial next phase → to move to precision tests of the isospin symmetry through spectroscopic methods that probe the wave functions across isobaric multiplets.

The total transition matrix element M = $\left\langle J_f M_f ; T_f T_z \middle| M^0_{jm} + M^1_{jm} \middle| J_i M_i ; T_i T_z \right\rangle$

with both isoscalar (M^0) and isovector (M^1) multipole operators.
Applying the Wigner-Eckart theorem ($T_f = T_i = T$)

$$M_{jm} = \frac{1}{\sqrt{2T+1}} \left[M^0_{jm} + \frac{T_z}{\sqrt{(T+1)T}} M^1_{jm} \right]$$

isoscalar isovector

for ΔT=0 transitions

$$M(T_z) = a + bT_z$$

matrix elements **linear** in Tz

Isospin "selection rules"

- **E1 transitions in mirror nuclei must be identical (no isoscalar component)**
- **E1 transitions forbidden in N=Z nuclei**
- **E2 transitions in T=1 isobaric triplets should lie on a line**

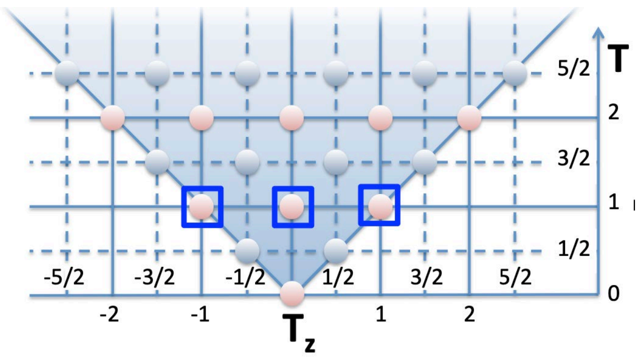
Linearity of E2 matrix elements

$$M(T_z) = a + bT_z$$

Can only be tested in multiplets of T ≥ 1

Ideal case: *B(E2)* for the $2^+_{T=1} \rightarrow 0^+_{T=1}$
Yields the proton matrix element, M_p

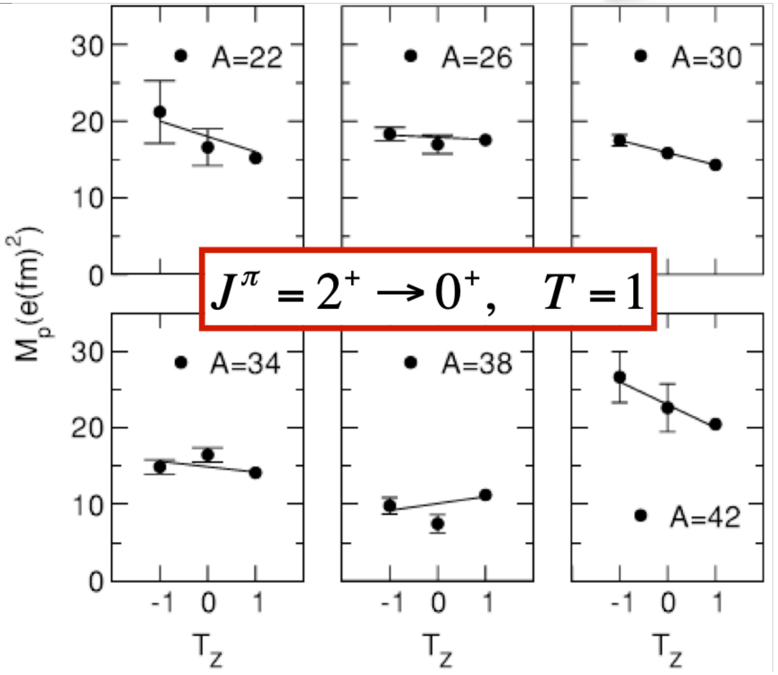
$$M_p = \sqrt{(2J_i + 1)B(E2, J_i \rightarrow J_f}$$



Bentley's triangle

Proton matrix element for isospin triplets:

Experimentally challenging



- High precision (e.g. lifetime) measurements required in exotic nuclei
- Systematic errors usually large (~10%)
- Isovector matrix element is small (not much variation with T_z)
- Odd-odd N=Z nuclei can be challenging

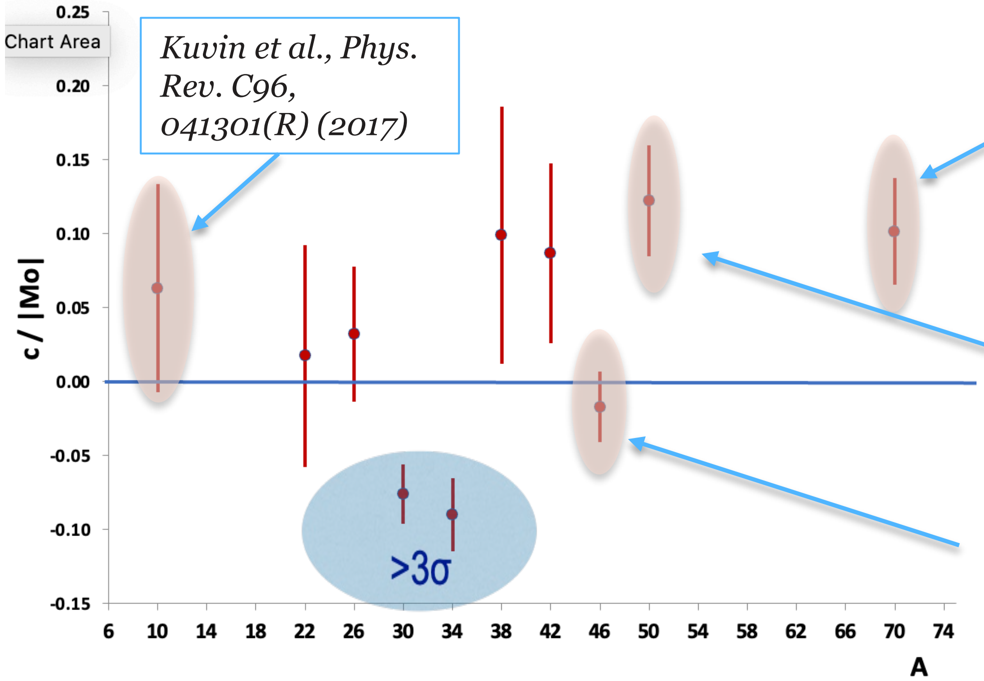
Testing the linearity in T=1 Triplets

Deviations can be measured through fitting quadratic function to the transition ME in a multiplet

- Requires B(Mλ) or B(Eλ) measurements in ≥ 3 members of a multiplet
- All 3 members of a T=1 Triplet (10 examples to date)
- 4 members of a T=3/2 Quartet (no examples!)

$$M(T_z) = a + bT_z + [cT_z^{\,2}]$$

From $B(E2, 2^+_{T=1} \rightarrow 0^+_{T=1})$
In all known T=1 triplets



Kuvin et al., Phys. Rev. C96, 041301(R) (2017)

K. Wimmer et al, Phys. Rev. Lett. 126, 072501 (2021)

M.M. Giles et al, Phys Rev. C 99, 044317 (2019) and C104 029901(E) (2021)

A. Boso et al. Physics Letters B 797 (2019) 134835

Compilation by Mike Bentley (2021)

Opportunities at LNL

Measure the B(E2) in isobaric triplets

Reactions with stable beams:

- Fusion-evaporation reactions (-2n evaporation channels)
- Reactions with solid ^{3}He targets (^{3}He,n)
- Selected cases may be done in multinucleon transfer with N=Z beam/target combinations utilizing PRISMA

AGATA: High-efficiency, gamma-gamma capability, position sensitivity (essential for high-velocity reactions and line-shapes)
NEDA: High-efficiency neutron detection

Doppler-shift methods: Lineshape analysis and Plunger-methods

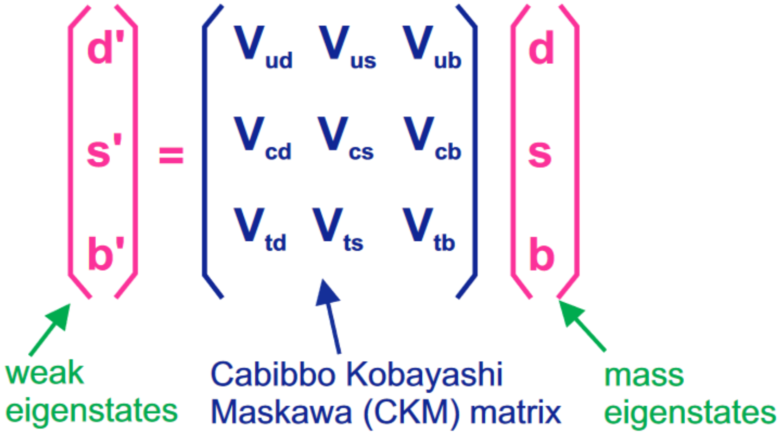
Cases chosen to aim for high-statistics high-precision measurements across multiplets (reduce systematic errors).

Fundamental interactions

Test the Standard Model:

Looking for «new physics»

Unitarity of the CKM three-generation quark mixing matrix



$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$?

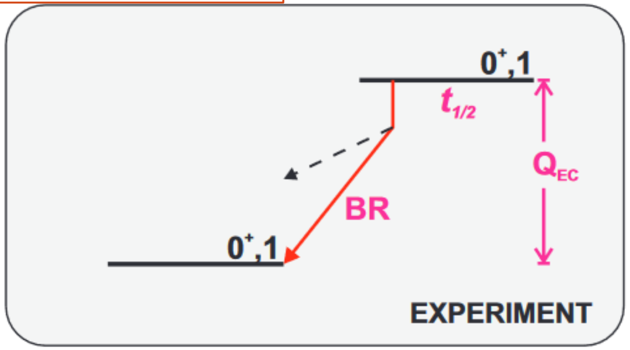
Information on V_{ud} can be obtained from:

- super-allowed Fermi beta decay
- free neutron lifetime
- mirror beta decay
- pion decay

super-allowed Fermi beta decay

From transition strength of super-allowed Fermi beta decay between nuclear analogue states of $I^\pi = 0^+$ $T = 1$: vector transition

- ➢ vector coupling constant



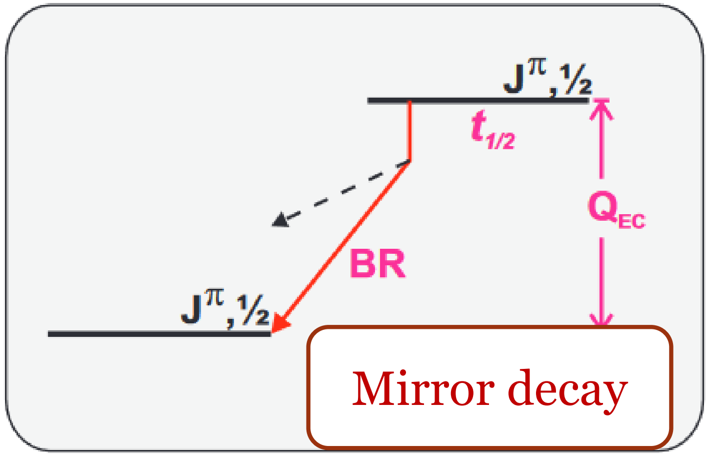
$$\mathcal{F}t \equiv ft(1+\delta'_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)}$$

Q $T_{1/2}$, BR ⟸ Experimental values

$$V_{ud} = \frac{G_V}{G_\mu}$$

These measurements have already arrived to a very good precision

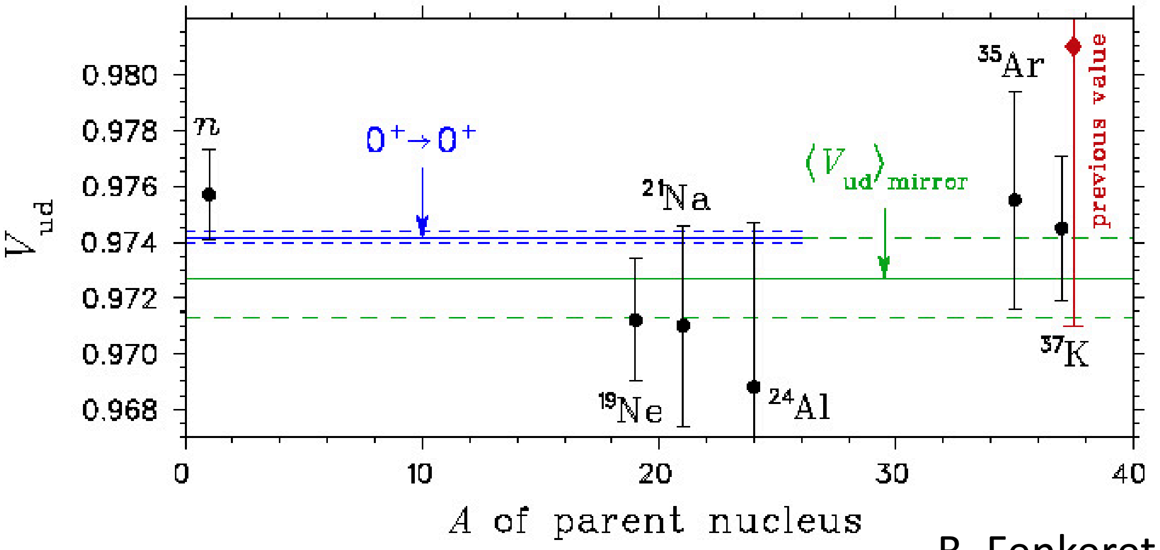
Mirror beta transitions



Involve the vector (Fermi) and the axial component of the weak current (Gamow Teller)

$$\mathcal{F}t = ft\,(1+\delta'_R)[1-(\delta_C-\delta_{NS})] = \frac{K}{G_V^2\,(1+\Delta_R)(1+\lambda^2\langle\sigma\tau\rangle^2)}$$

$\lambda = G_A/G_V$



From mirror decay:

V_{ud} (T=1/2)= 0.9727 + 0.0014

From super-allowed:

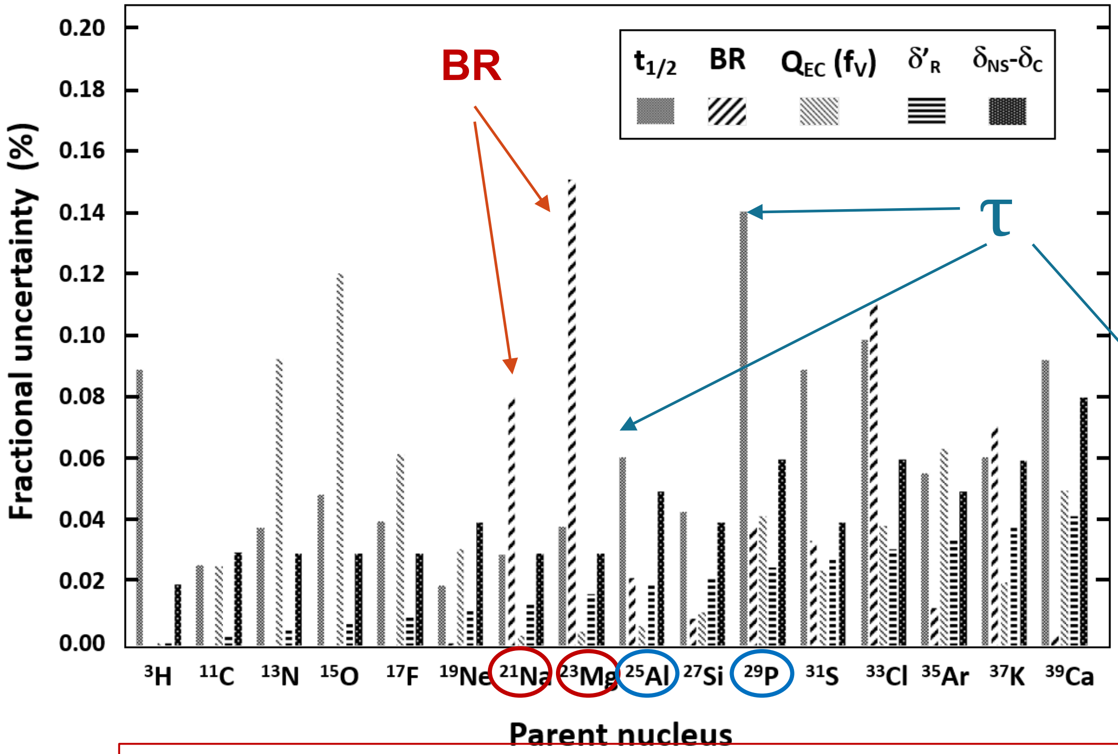
V_{ud} ($0^+ \rightarrow 0^+$)= 0.9742 + 0.0002

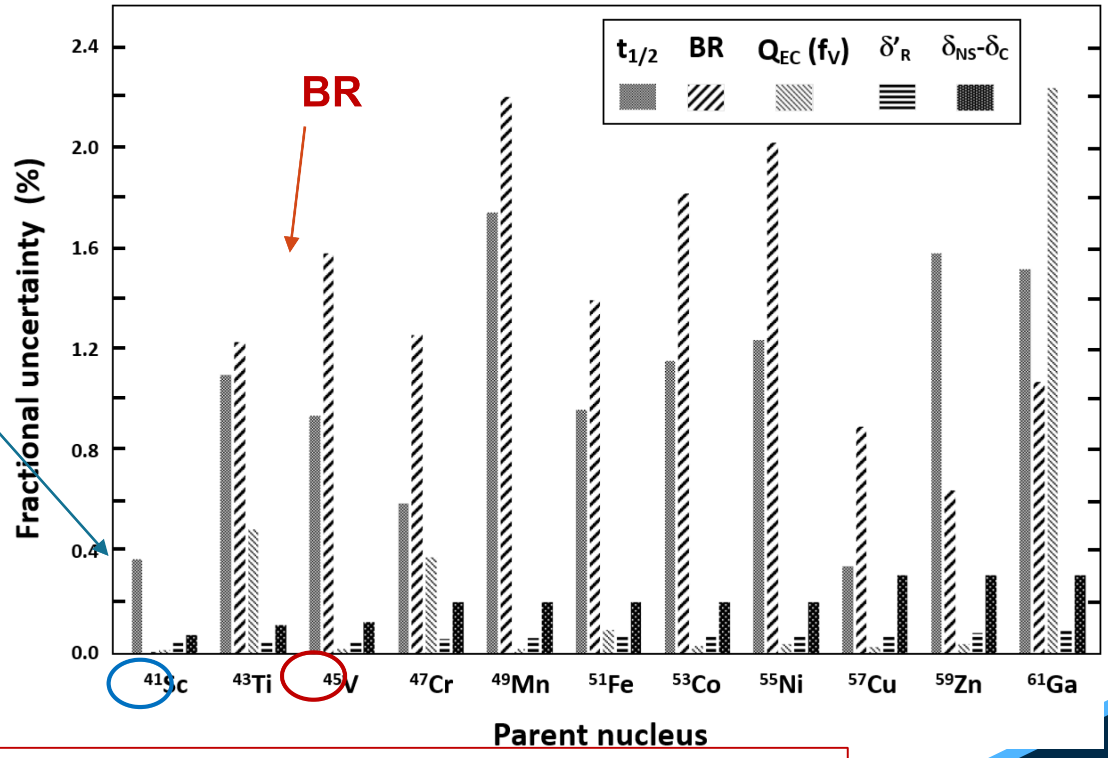
B. Fenkeret al., Phys. Rev. Lett. 120, 062502 (2018)

Precision measurements to look for new physics

Fractional contribution of the experimental and theoretical input factors to the error of mirror ***Ft*** values

N. Severijns et al. arXiv: 2109.08895v1



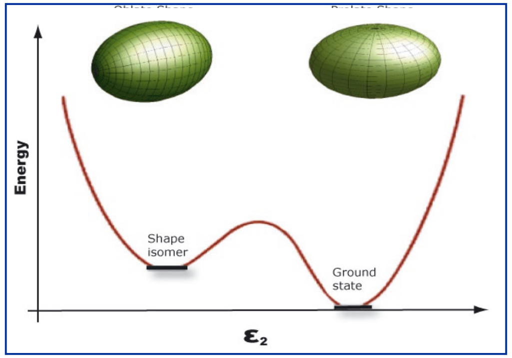


Precision measurements of the branching ratio and/or lifetimes at the beta-decay station with SiC and TiC targets in SPES

Perspectives with N~Z nuclei

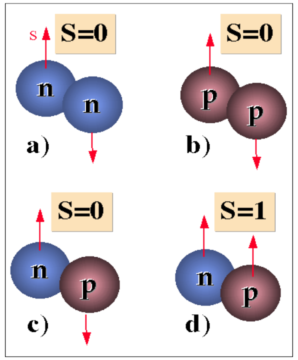
Understanding the nuclear interaction

Shapes and shape coexistence



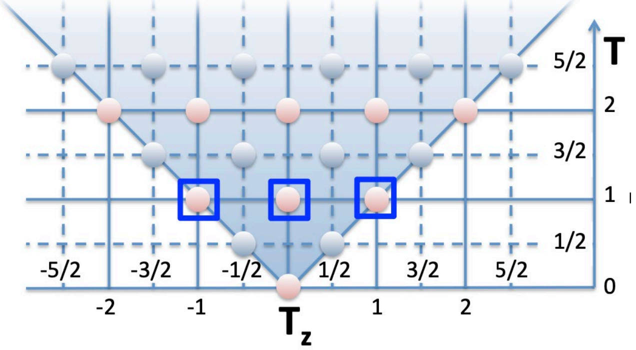
Lifetime measurements of excited states in N~Z nuclei
Stable beams
AGATA + NEDA + plunger

pn T=0 paring and quarteting



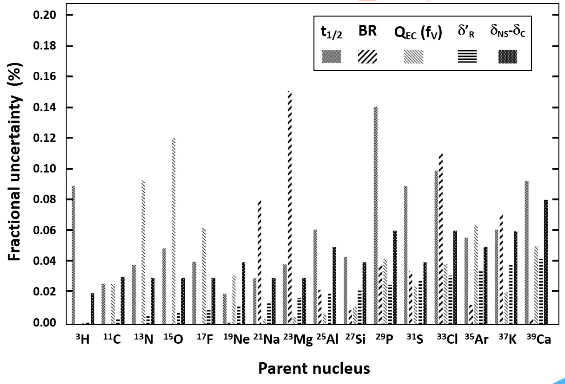
Transfer reactions (^{3}He,p), (^{4}He,d), (^{6}Li,d)
Stable beams (*sd* shell)
SPES beams (*fp* shell)
GRIT+ Ge det + recoil det.

Isospin symmetry breaking



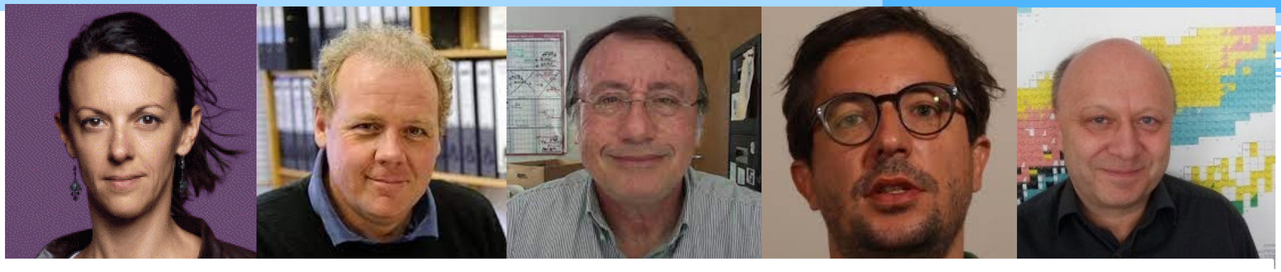
Lifetime measurements of the 2+ state in T=1 isobaric triplets
Stable beams
AGATA + NEDA + plunger

Search of new physics with Mirror beta decay



Lifetime and BR measurements in mirror beta decay
SPES Beams
Beta-deacy station +
Beta + Ge det.

Thank you!



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