NUSTAR Annual Meeting 2013
GSI, Darmstadt
February 28 (25-March 1), 2013

Quest for signatures of tensor and other forces

– A proposal for relativistic heavy-ion beam facility –

Takaharu Otsuka
University of Tokyo / MSU

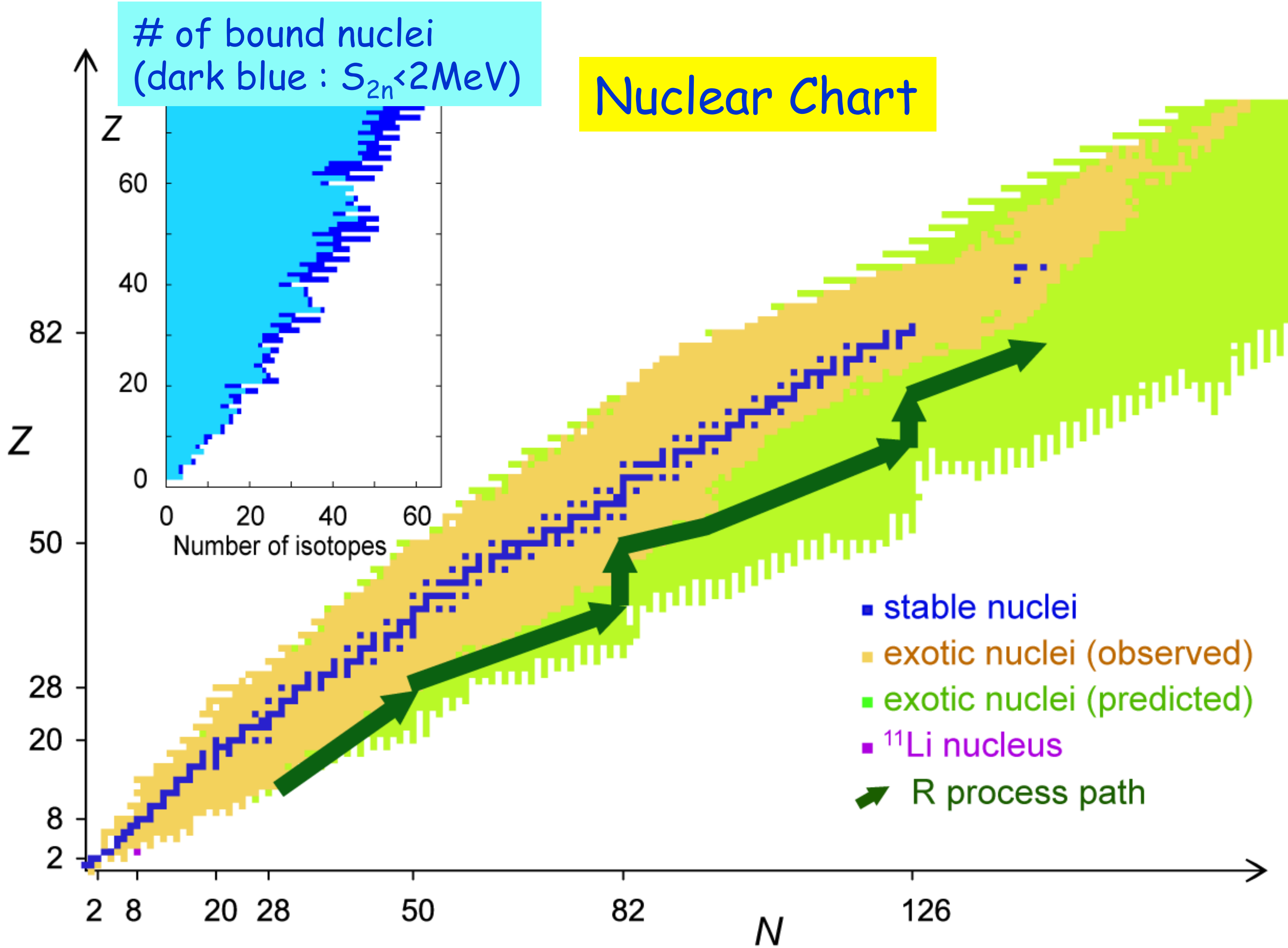
HPCI Strategic Programs for Innovative Research (SPIRE)
Field 5 "The origin of matter and the universe"

10:03 PM

Outline

1. Introduction
2. Shell evolution due to nuclear forces
3. Experimental signatures of tensor-force driven shell evolution
4. Relativistic Coulomb Excitation
5. Three-body forces
6. Summary

Nuclear Chart



Theoretical prediction :
Koura *et al*. Prog. Theor. Phys. **113**, (2005) 305.

One of the primary objects can be
to look for paradigm shifts in the understanding of the structure (and reactions) of exotic nuclei
in comparison to the structure of stable neuclei,
i.e., densities, magic numbers, shapes, …

Nuclear Physics News

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gnpn20

Shell Evolution in Exotic Nuclei and Nuclear Forces

Takaharu Otsuka [a b] & Achim Schwenk [c d]

Physica Scripta

An international journal for experimental and theoretical physics

Nobel Symposium 152: Physics with Radioactive Beams

Exotic nuclei and nuclear forces   T. Otsuka

http://iopscience.iop.org/1402-4896/2013/T152/014007

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Monopole component of tensor force

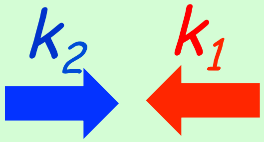
- An intuitive picture -

TO, Suzuki, et al.
PRL 95, 232502

At collision point:

$$\Psi \propto e^{ik_1x_1}e^{ik_2x_2} + e^{ik_2x_1}e^{ik_1x_2} = 2\,e^{iKX}\cos(kx)$$

$$k = k_1 - k_2\,, \quad K = k_1 + k_2$$

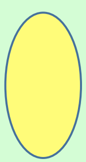


large relative momentum k

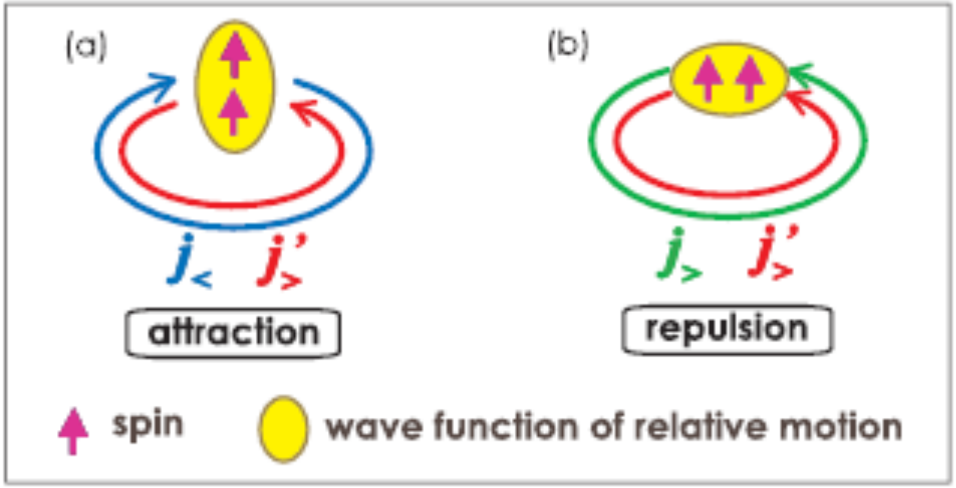
⇩

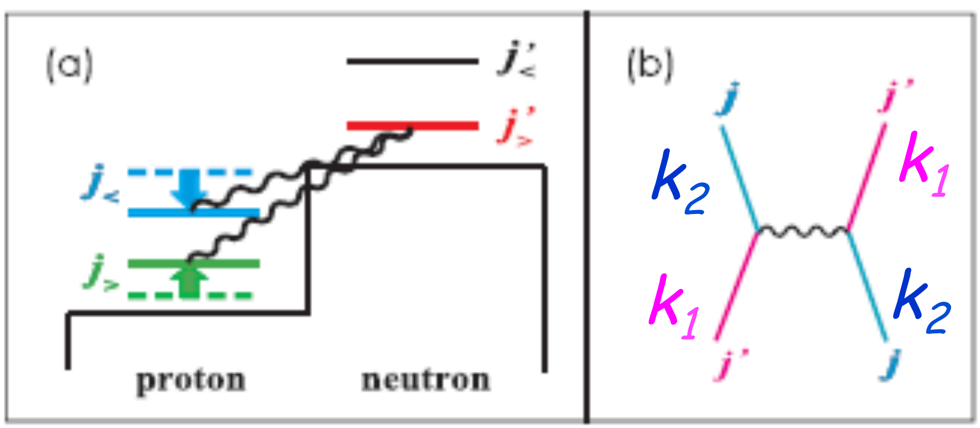
strong damping

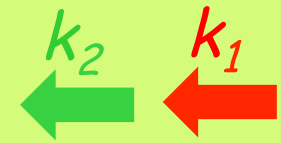
⇩



wave function of relative coordinate





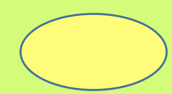


small relative momentum k

⇩

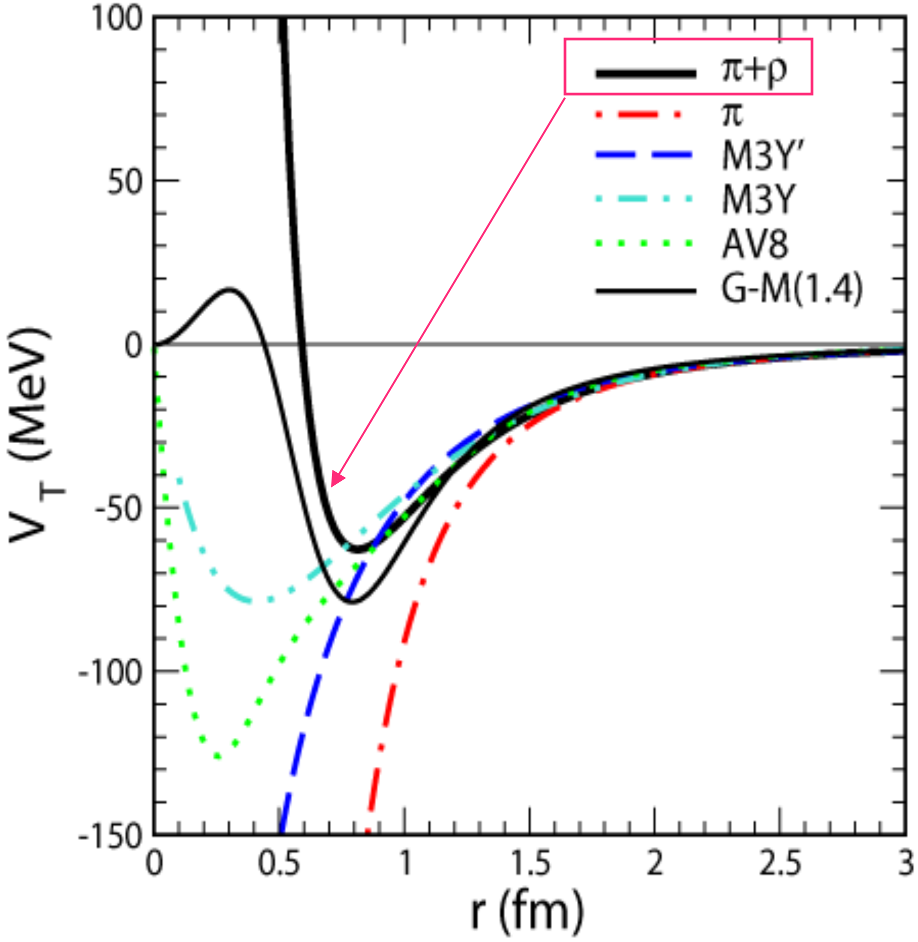
loose damping

⇩

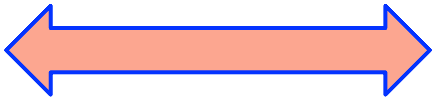


wave function of relative coordinate

Tensor potentials



What is the
relevant part of the
tensor force
to the present issue.



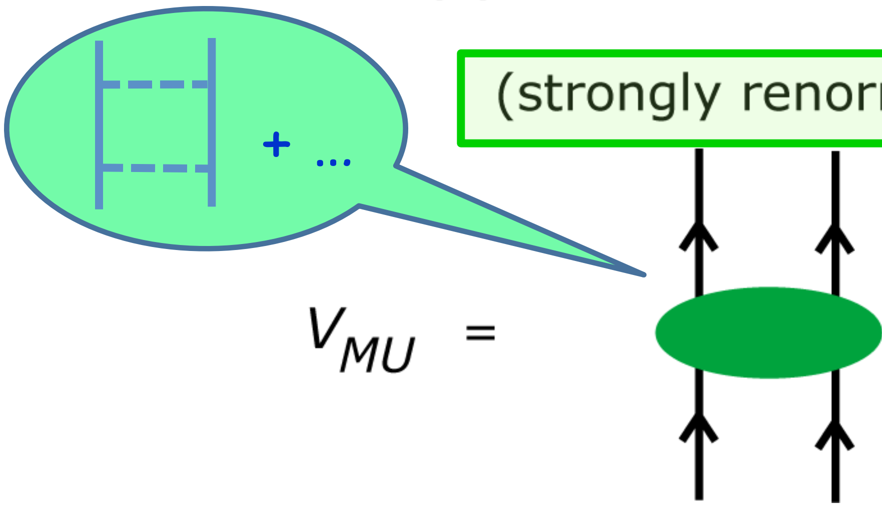
medium-long range

Two major components in two-body nuclear force

(a) central force :

(strongly renormalized)

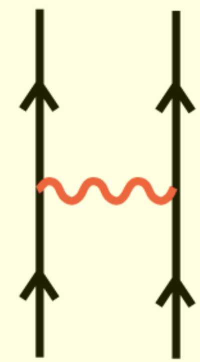
V_{MU} =



\+

(b) tensor force :

π + ρ meson exchange



in nuclear medium

almost equal

in free space

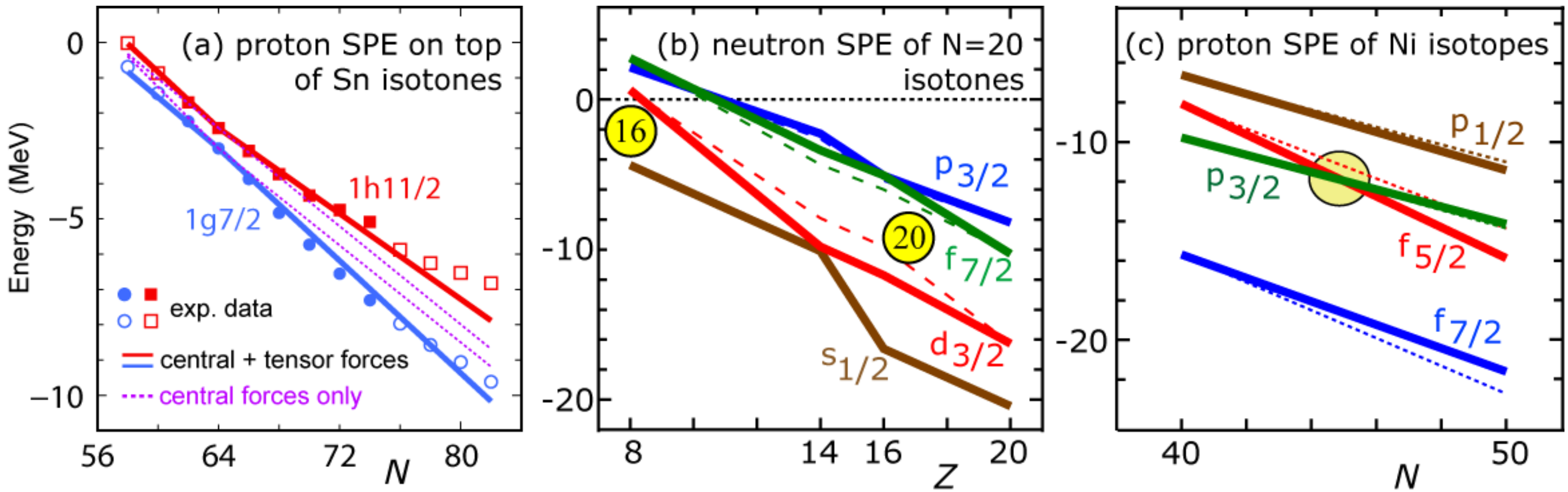
PHYSICAL REVIEW C 84, 044322 (2011)

Renormalization persistency of the tensor force in nuclei

N.Tsunoda, T.O., K.Tsukiyama, M.H.-Jensen

Shell evolution due to the tensor + central forces almost everywhere on the nuclear chart

From NuPECC News, Dec. 2012



Proton orbits on top of Sn core.

Emerging of magic number *N*=16, and disappearance of *N*=20.

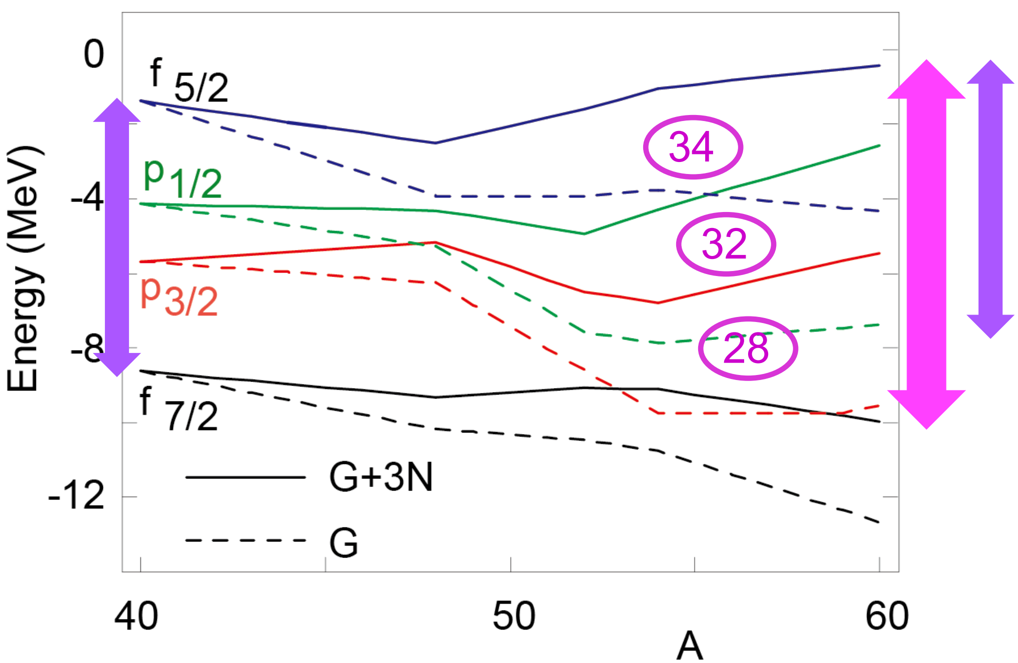
Weakening of *Z*=28 gap and crossing between $f_{5/2}$ and $p_{3/2}$
-> exotic Ni isotopes

3-body forces does produce another shell evolution

Ca isotopes

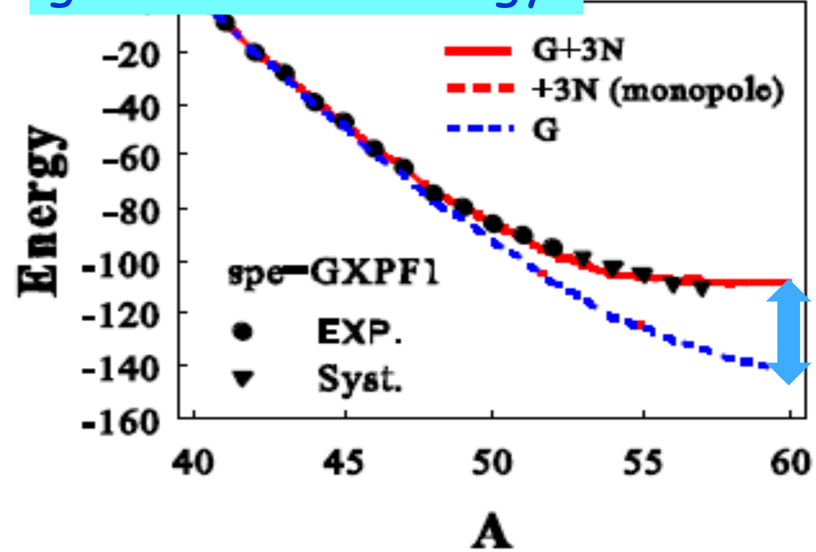
Nuclear Structure and Dynamics 2012 Proceedings, Suzuki, Otsuka and Honma

Neutron single-particle energy of Ca isotopes



2 MeV widening of $f_{7/2}$ - $f_{5/2}$ gap

ground state energy



G-matrix
3rd order Q-box
24 hw int. states
3NF : Fujita-Miyazawa

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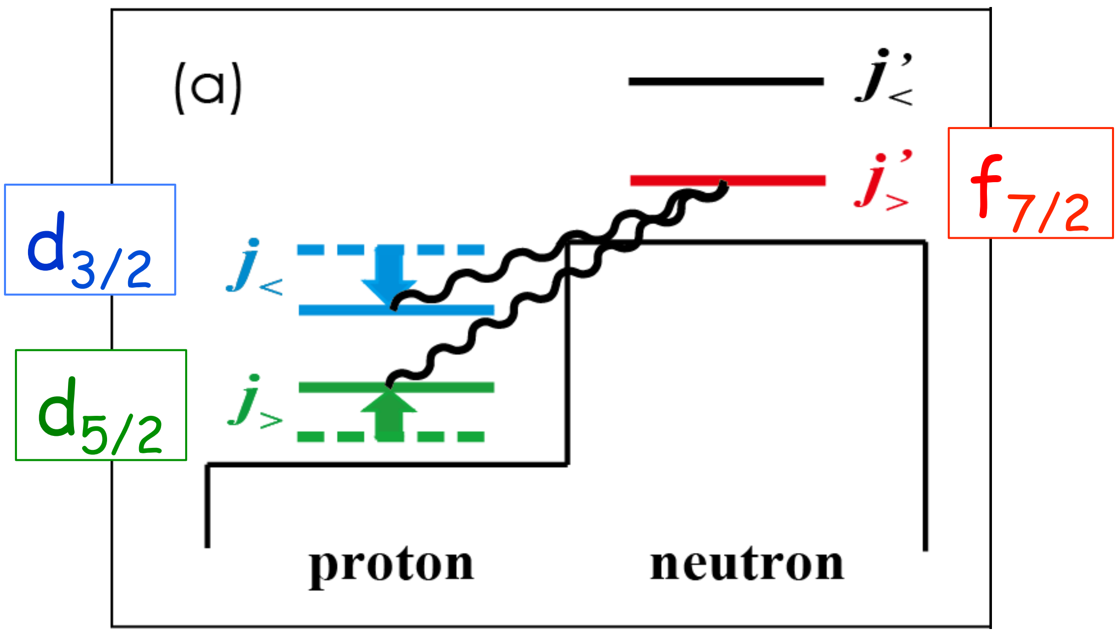
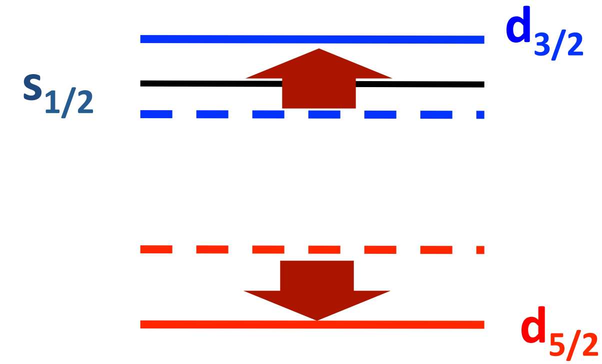
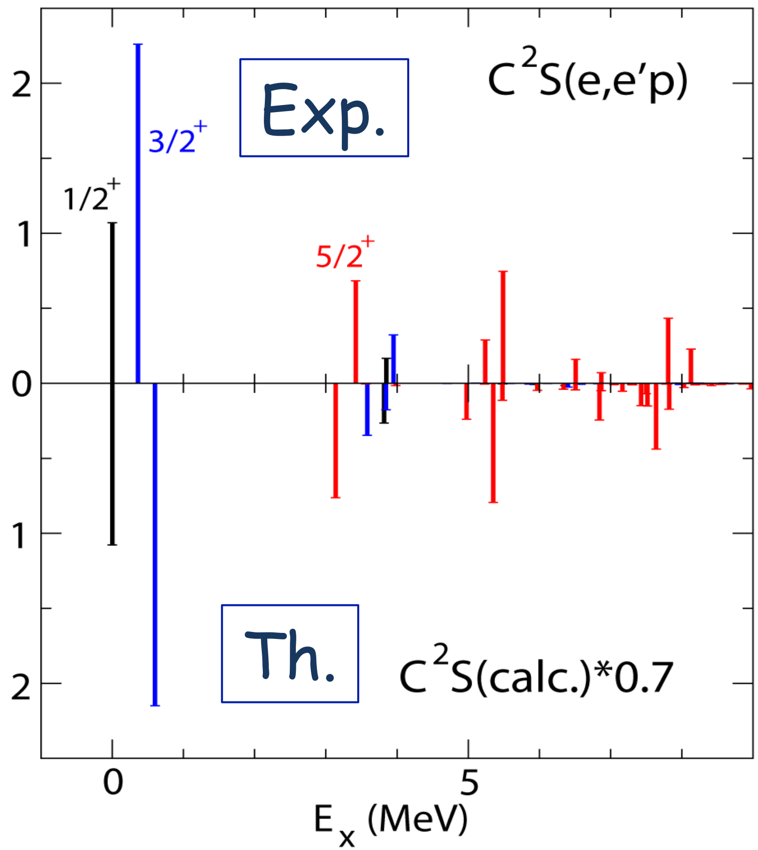

(a)
$j'_<$
$j'_>$
$f_{7/2}$
$d_{3/2}$
$j_<$
$d_{5/2}$
$j_>$
proton
neutron

Spectroscopic factors obtained by (e,e'p) on ^{48}Ca

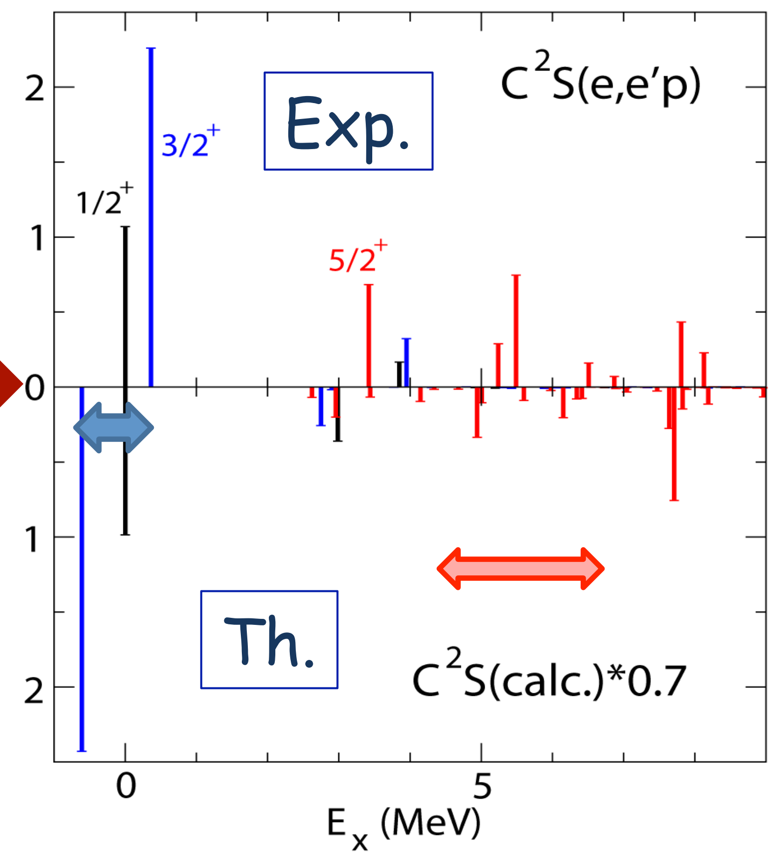
(Kramer et al., NP A679, 267 (2001) NIKHEF)



with full tensor force



no tensor in the cross shell part



Utsuno, Otsuka, *et al.*, Phys. Rev. C (2012)

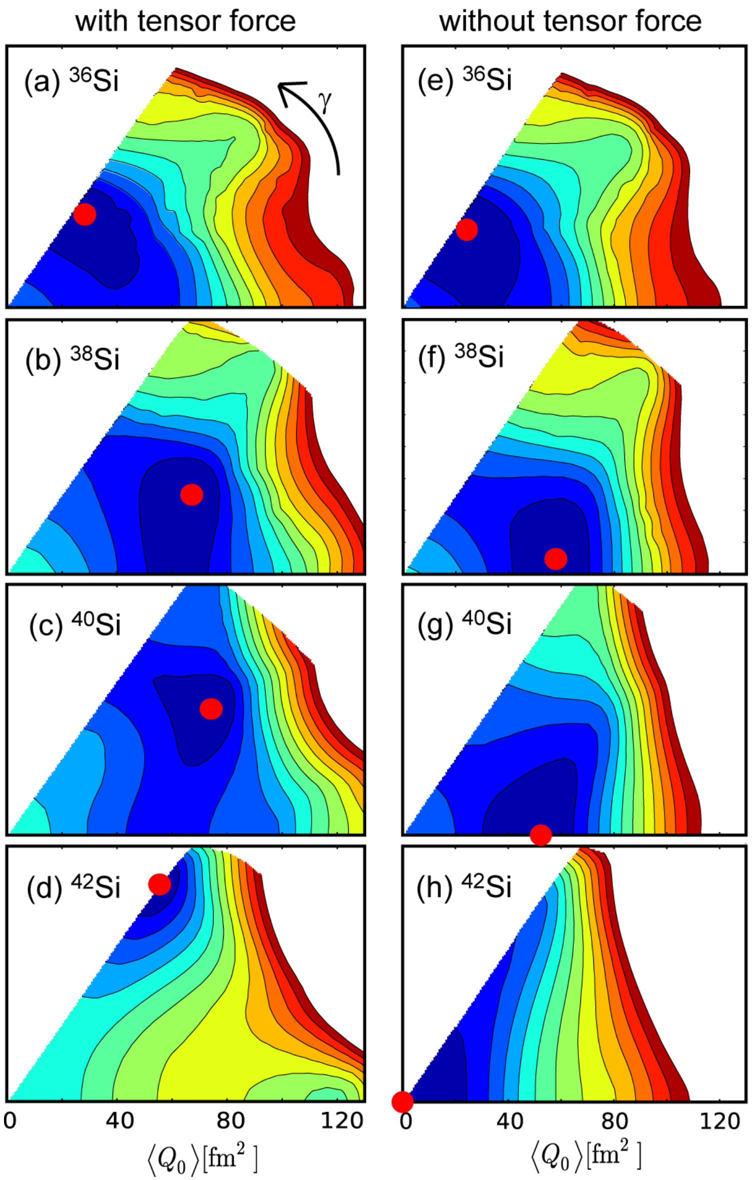
Exotic Si and S isotopes

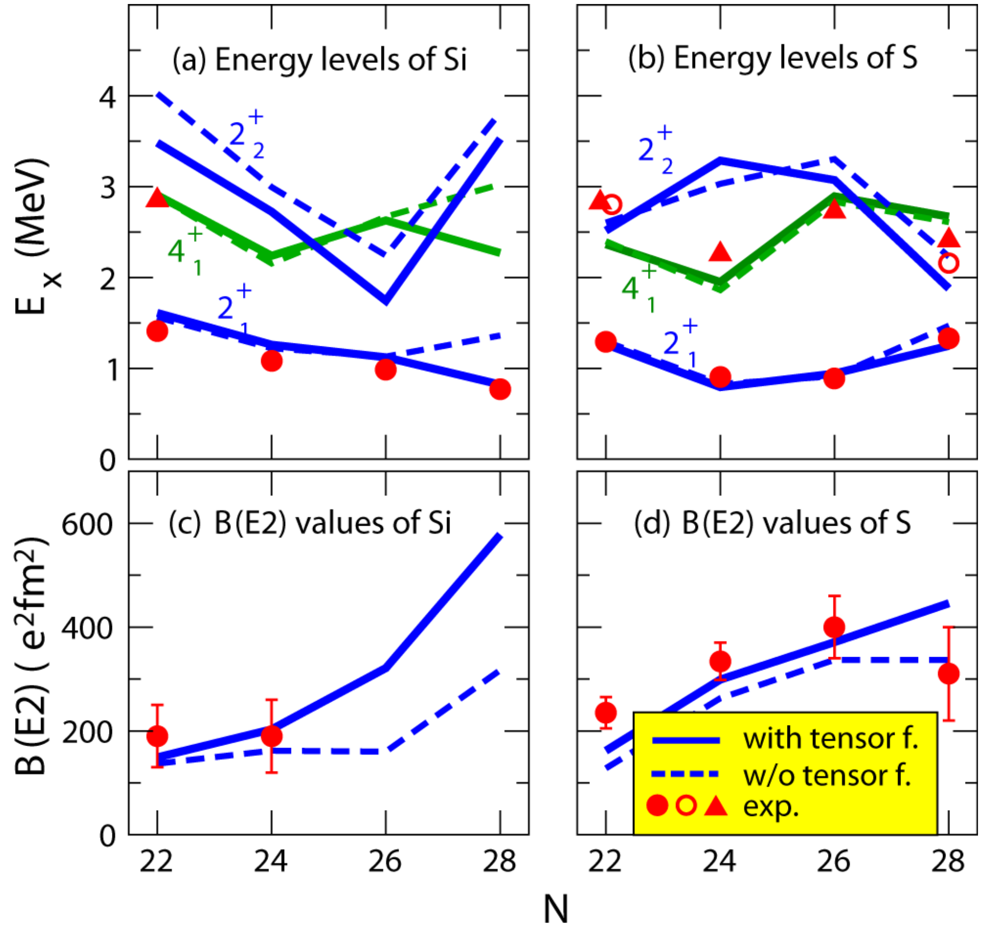
Utsuno, Otsuka, *et al.*, Phys. Rev. C (2012)

Shapes (PES)

Levels and B(E2)'s

Si





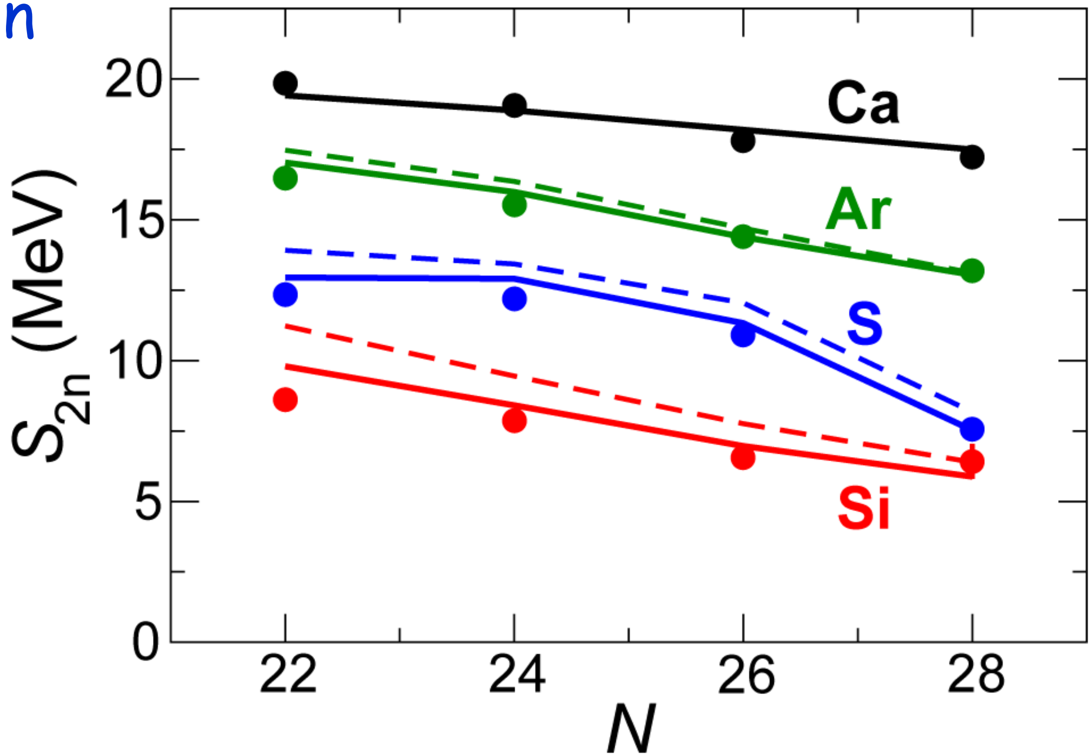
—— with cross shell (p-n) tensor force

– – – without it

Mass

Two-neutron separation energy

Effect of tensor force on binding energies



with cross shell (p-n) tensor force

without it

Utsuno, Otsuka, *et al.*, Phys. Rev. C Rapid (2012)

Signatures of the tensor-force driven shell evolution

Single-particle strength distributions by (e,e'p), ...
within stable nuclei ... in future ?

Level structure and E2 properties
by gamma-ray spectroscopies with various methods
for exotic nuclei

Mass measurements of exotic nuclei

What about M1 excitation ?

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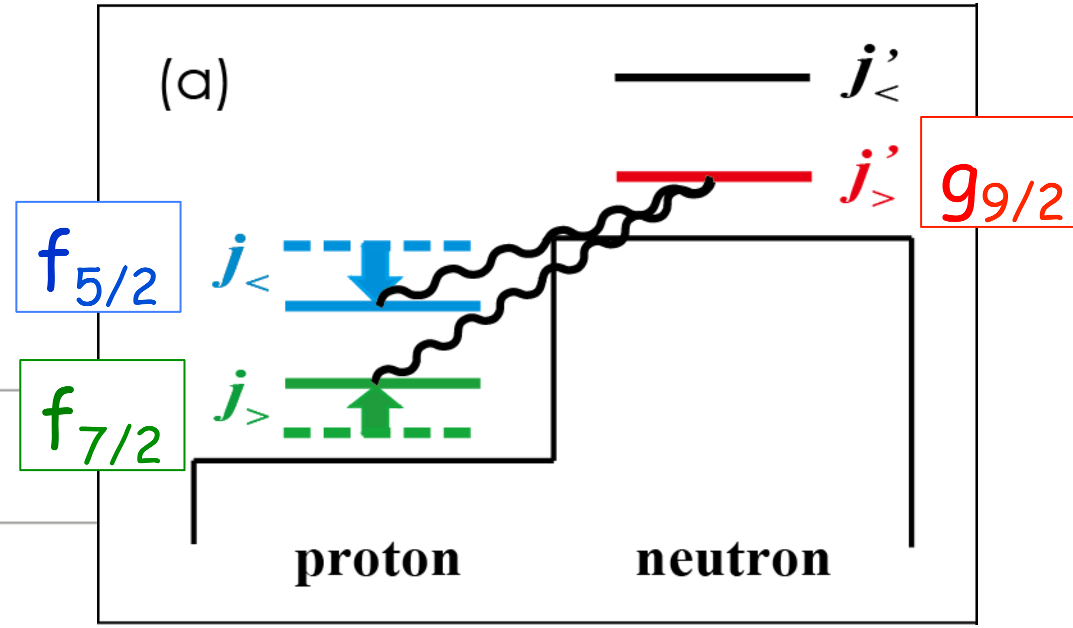
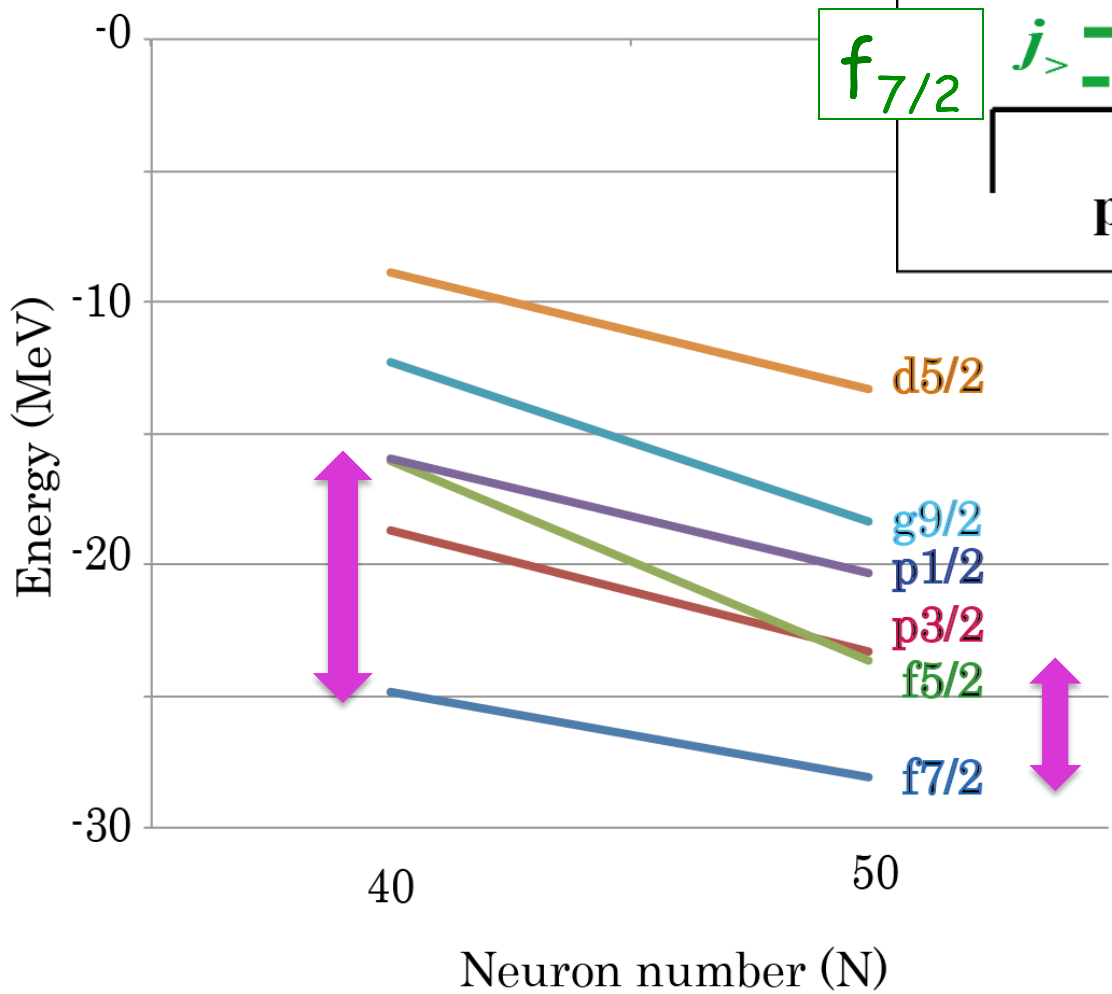
Example of exotic Ni isotopes

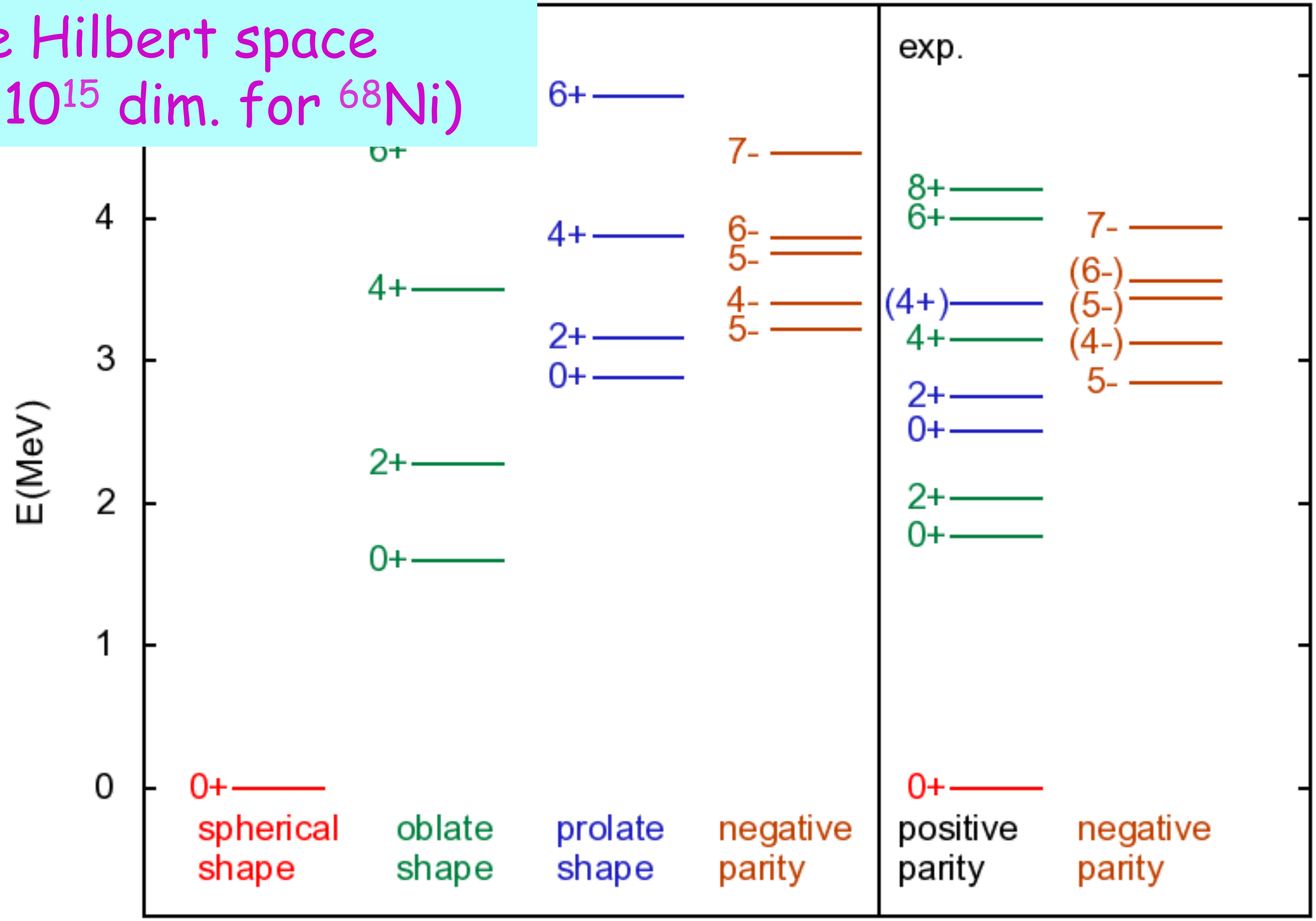


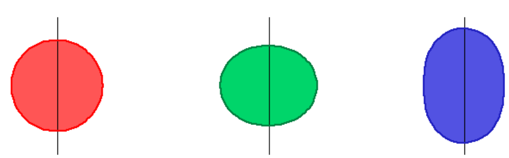


Single-particle energies obtained from a new shell model Hamiltonian

Level scheme of ^{68}Ni

Monte Carlo Shell Model
large Hilbert space
(5×10^{15} dim. for ^{68}Ni)

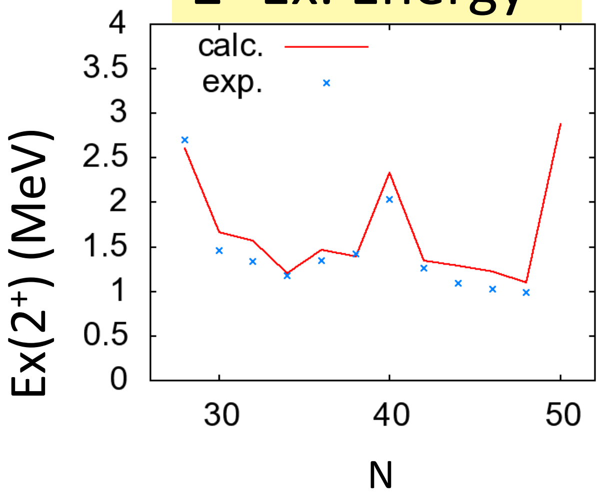




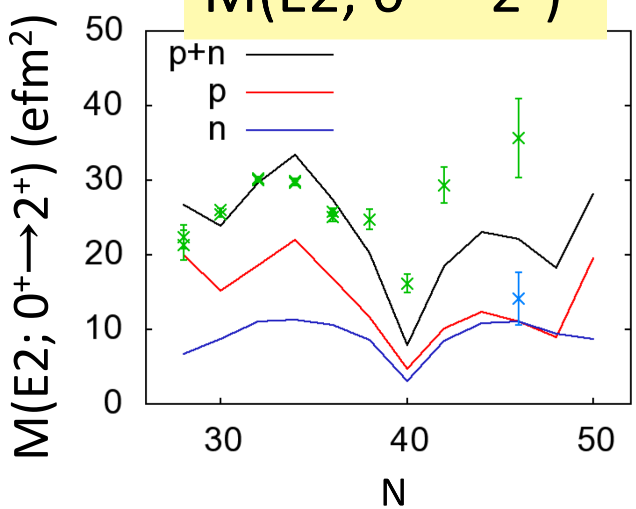
Broda et al., submitted

Systematic description of $^{56,68,78}Ni$

2^+ Ex. Energy



M(E2; $0^+ \rightarrow 2^+$)

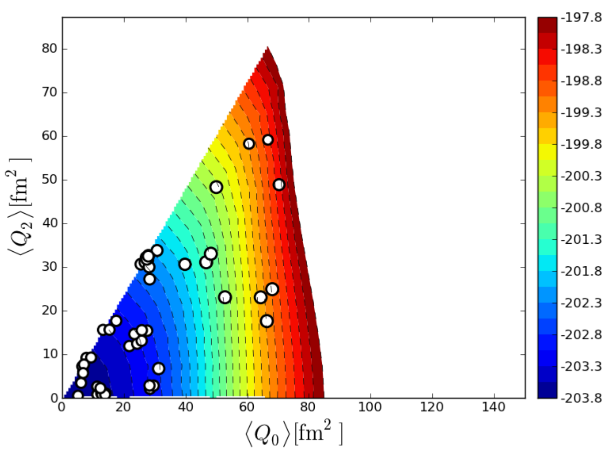


× B. Pritychenko, et al., arXiv:1102.3365v2 (2011)

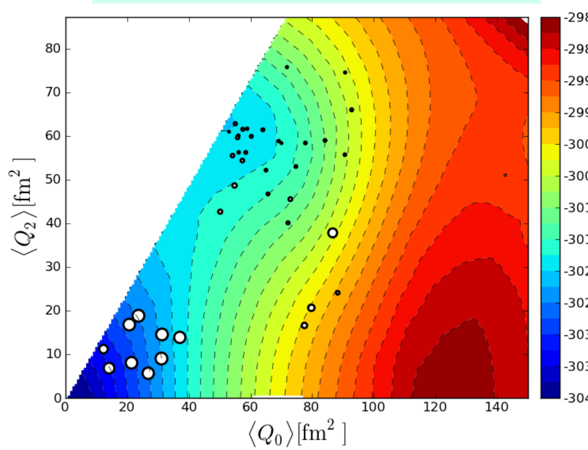
× de Angelis, private communication

Basically spherical ground state

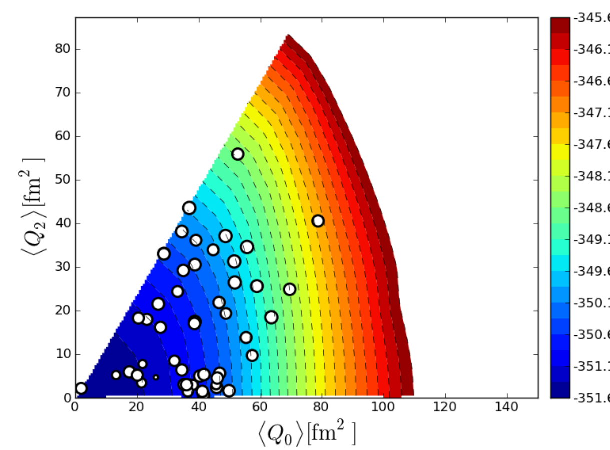
0^+_1 state of ^{56}Ni



0^+_1 state of ^{68}Ni



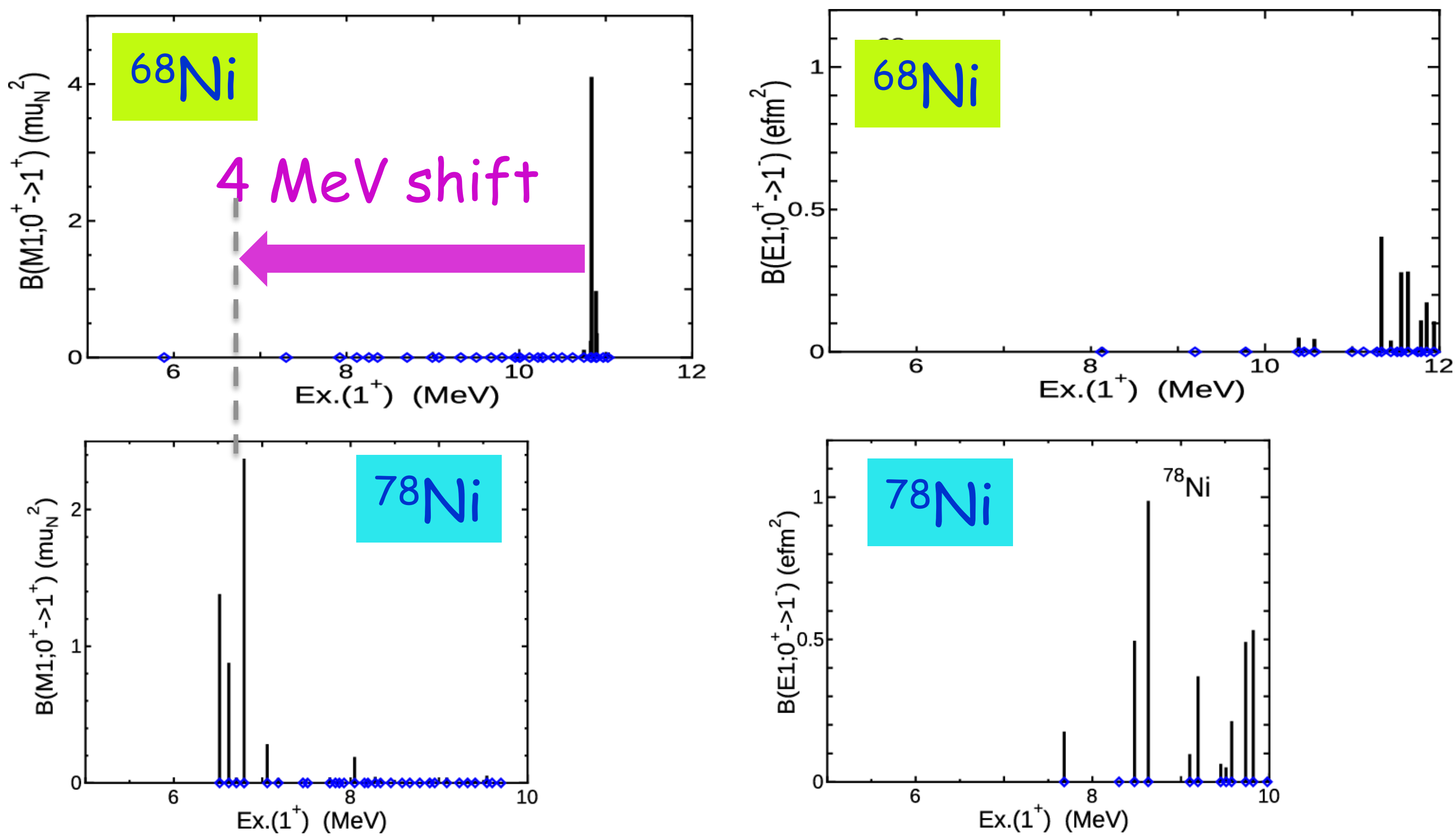
0^+_1 state of ^{78}Ni



M1 and E1 excitations from the ground state

M1
dominated by proton $f_{7/2}$ -> $f_{5/2}$

E1 (only Pygmy part)



Clean spectra if E2 is invisible

(γ, γ') is a good tool to see M1 excitations for stable nuclei

Bohle, Richter, *et al.*

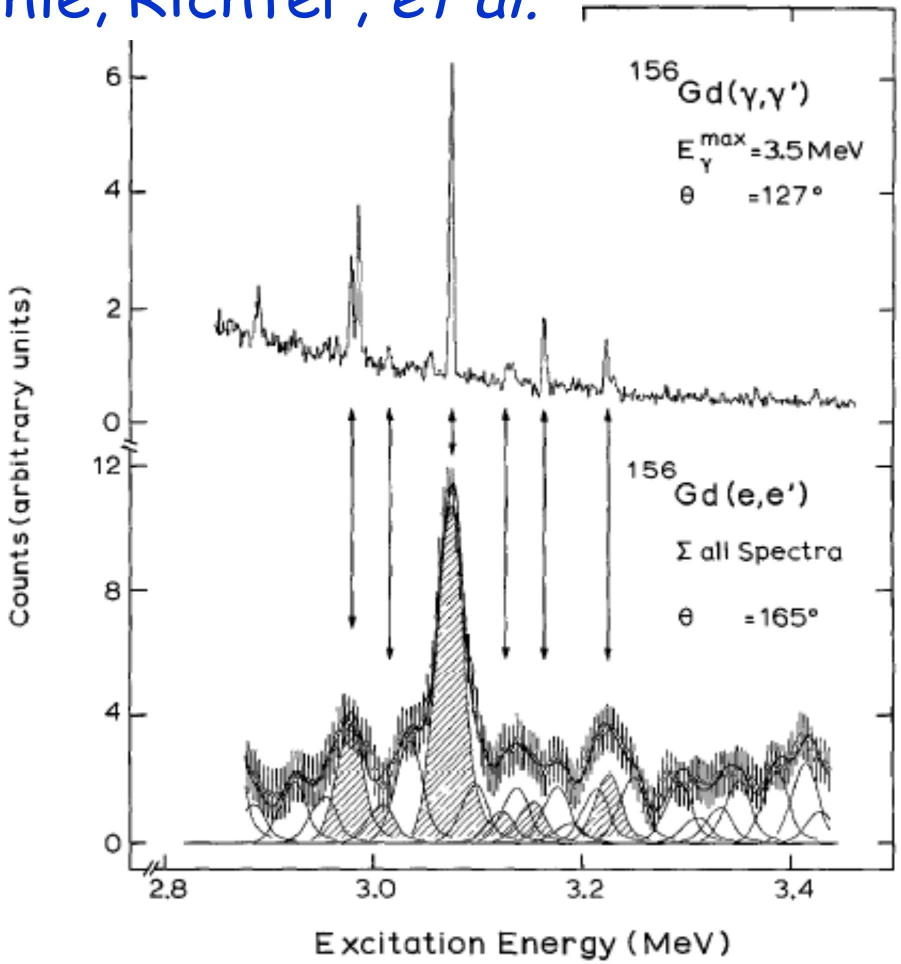


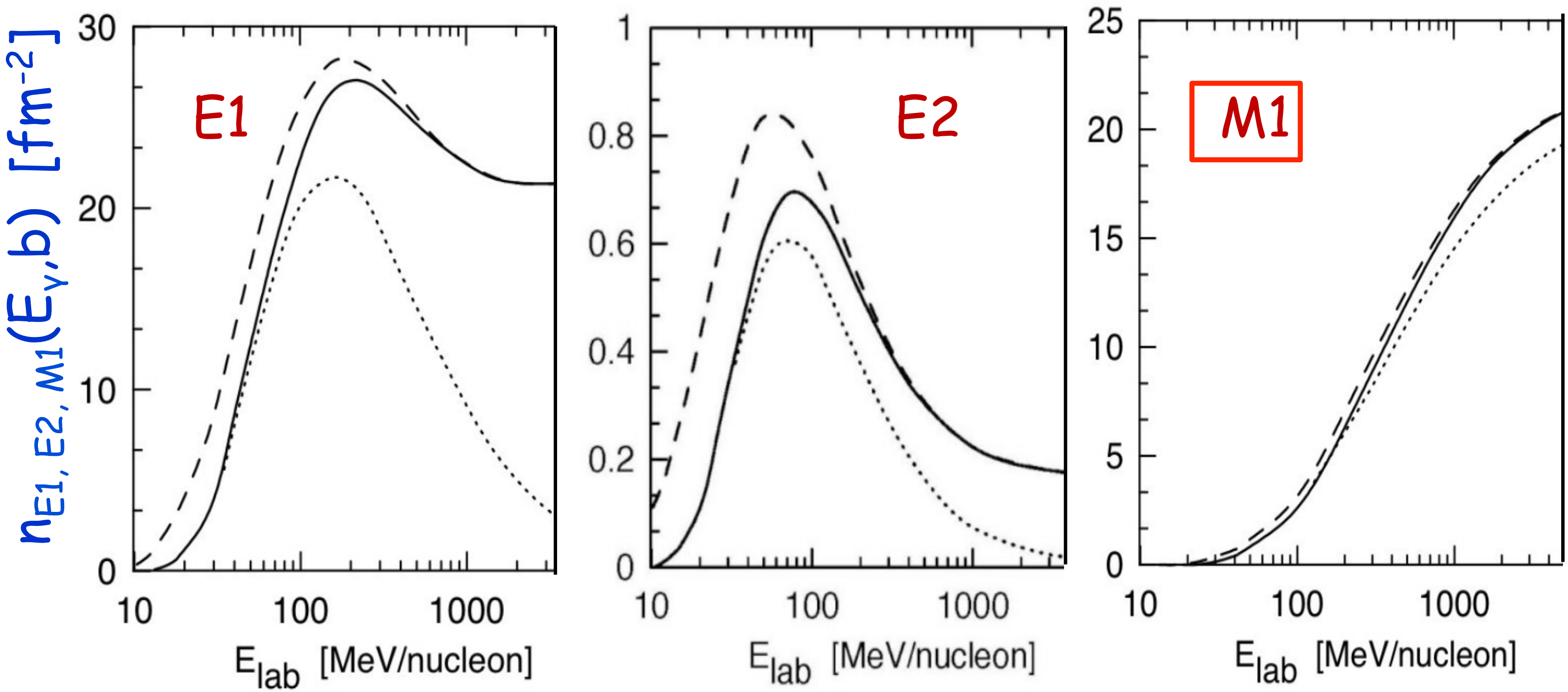
Fig. 2. Comparison of NRF and electron scattering spectra in the region of the new M1 mode where corresponding peaks have been marked by arrows. Note, that peaks from inelastic and elastic scattering occur simultaneously in the gamma ray spectrum.

Nuclear Physics A458 (1986) 205–216

Limited to stable nuclei

Relativistic Coulomb Excitation in a Heavy Ion Collision

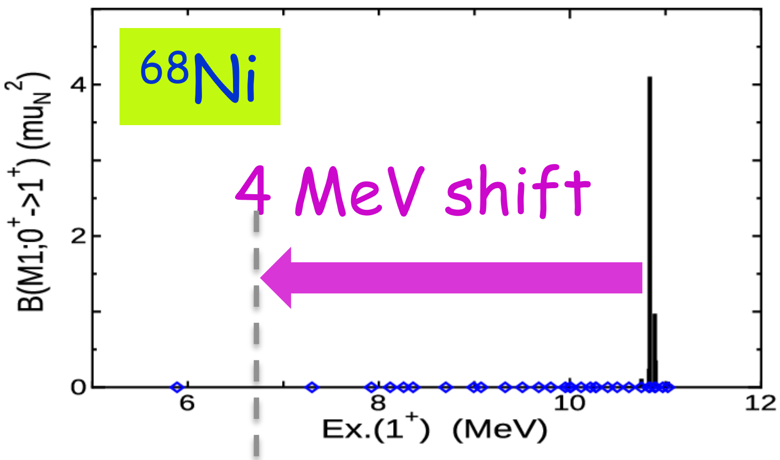
A.N.F. Aleixo and C.A. Bertulani; Nucl. Phys. **A505** (1989) 448
C.A. Bertulani; Lecture Notes at the 8th CNS-EFES Summer School

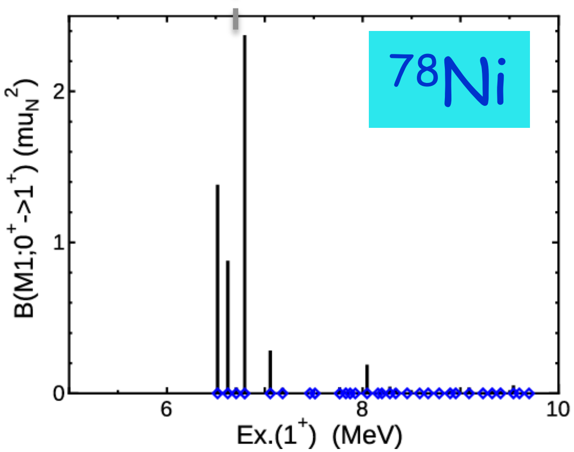


Electric dipole number of equivalent photons per unit area $2\pi b \cdot db$ with energy of 10MeV, incident on ^{208}Pb in a collision with ^{16}O at b=15fm for E1, E2 and M1

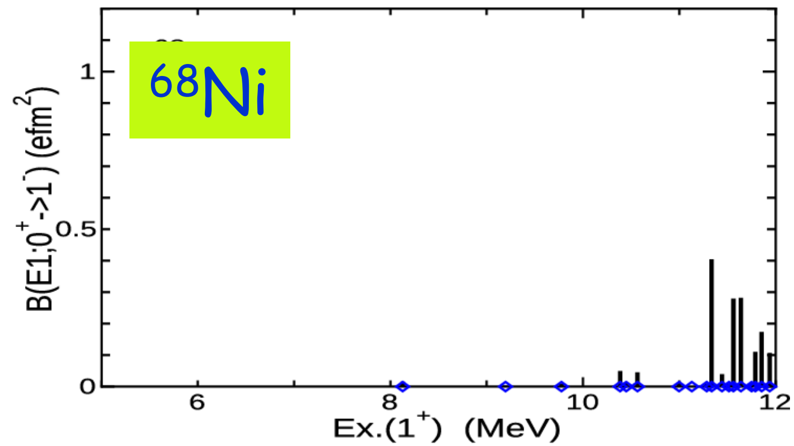
Relativistic Coulomb excitation : a very promising tool

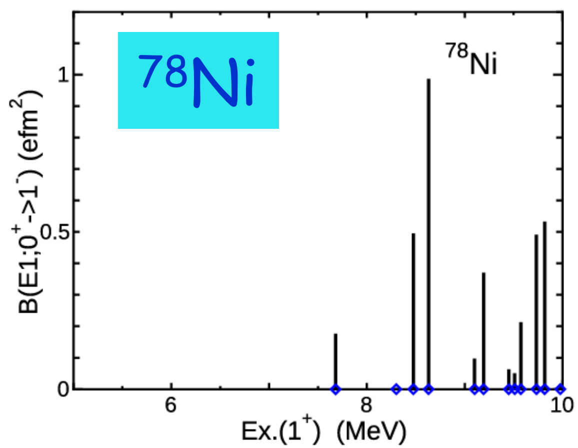
M1
dominated by proton $f_{7/2} \rightarrow f_{5/2}$





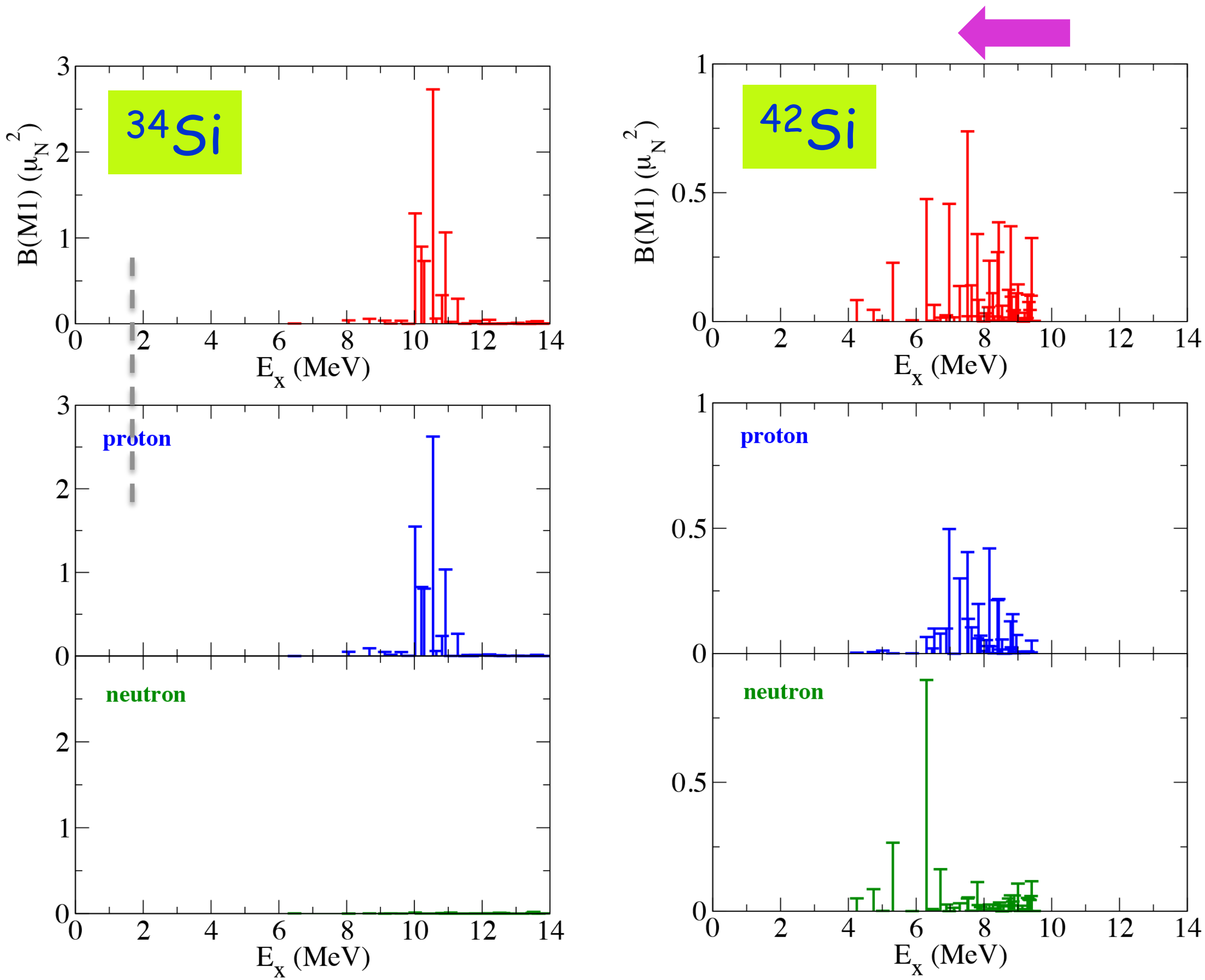
E1 (only Pygmy part)





Clean spectra because E2 is suppressed

M1 excitations from the ground state of Si isotopes



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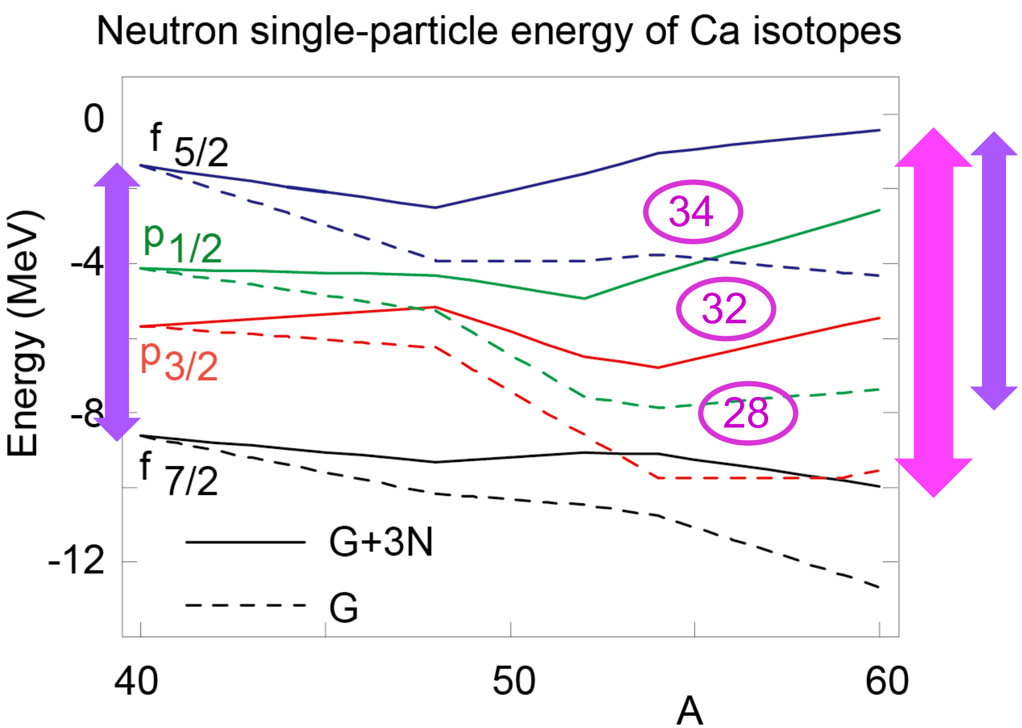
3-body forces does produce another shell evolution

Ca isotopes

Nuclear Structure and Dynamics 2012 Proceedings, Suzuki, Otsuka and Honma



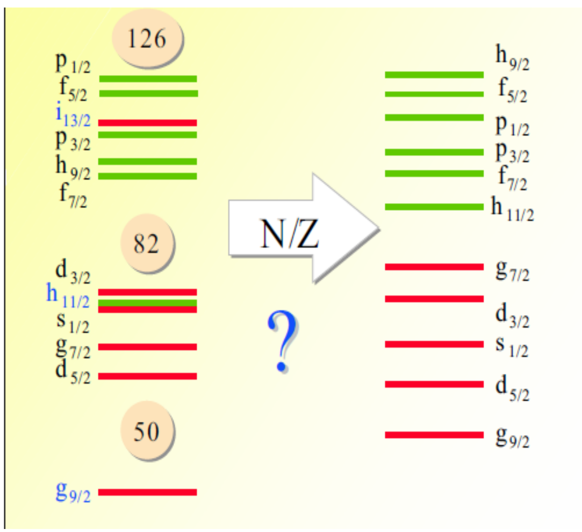
2 MeV widening of $f_{7/2}$ - $f_{5/2}$ gap

Opposite trend compared to shell quenching

Caution : drip line may be still far

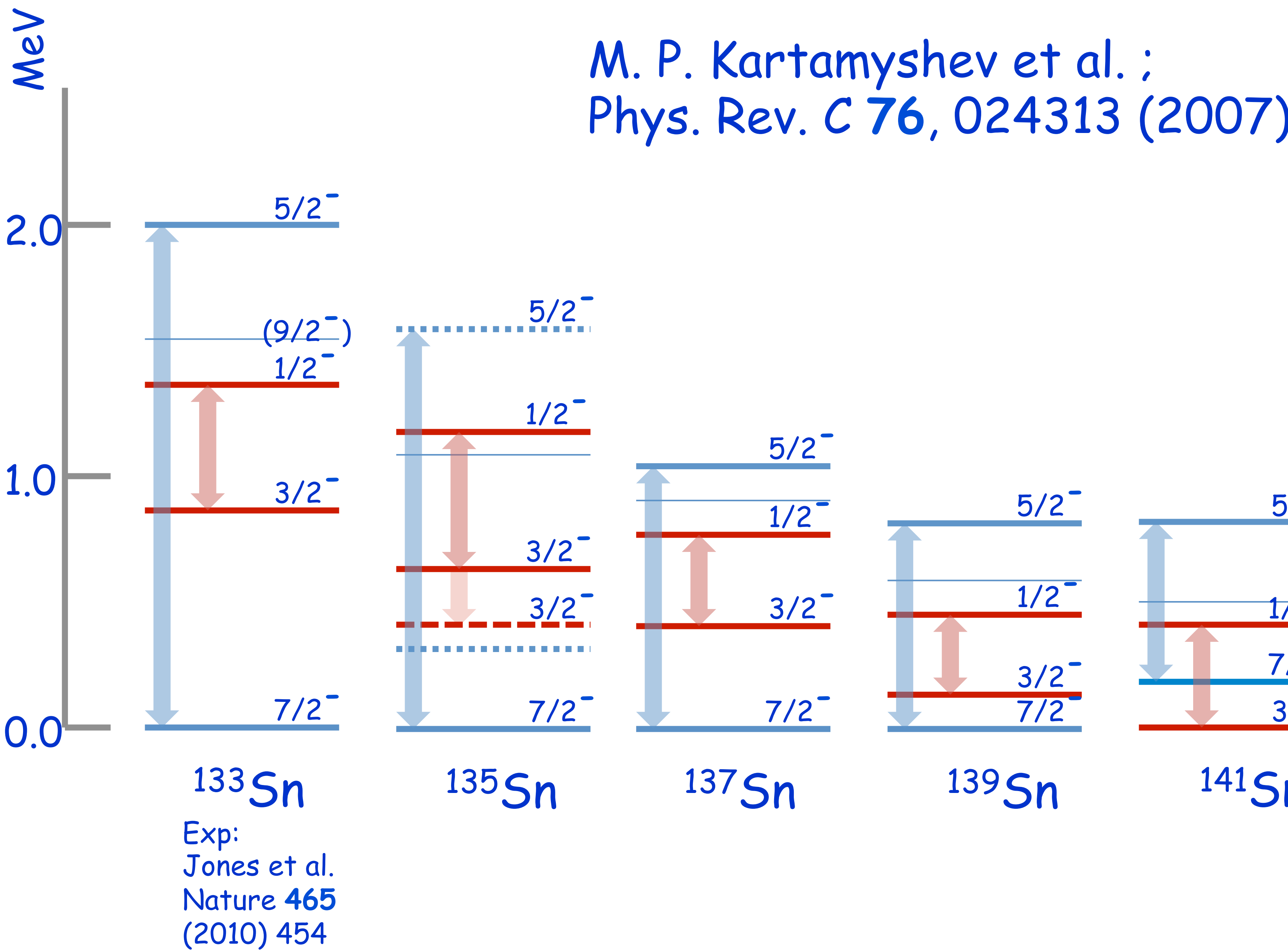
G-matrix
3rd order Q-box
24 hw int. states
3NF : Fujita-Miyazawa

From RIA Physics White Paper



shell structure. The bunching of the energy levels that is endemic to shell structure depends on the form and the shape of the average mean field potential in which the hadrons are moving. With a diffuse surface region, the spin-orbit force may be weakened. Some

Is this the primary change ?


MeV
M. P. Kartamyshev et al. ;
Phys. Rev. C 76, 024313 (2007)
2.0
1.0
0.0
5/2⁻
(9/2⁻)
1/2⁻
3/2⁻
7/2⁻
133Sn
135Sn
137Sn
139Sn
141Sn
Exp:
Jones et al.
Nature 465
(2010) 454

Summary

1. Noveltiesand paradigm shifts due to nuclear forces on the structure of exotic nuclei

2. Tensor force and three-body force change the spin-orbit splitting.

3. M1 transitions between spin-orbit partners is one of ideal tools to see this.

4. For stable nuclei, M1 excitations have been measured by (γ, γ') experiments.
   But, this is infeasible for exotic nuclei.

5. Relativistic Coulomb excitations are its analog for exotic nuclei

6. Shifts of several MeV of major peaks by the shell evolution predicted. This is a basic trend, independent of details.

7. Other interesting cases with shell evolution by three-body forces

Collaborators

W. Henning	Munich/ANL/RIKEN	*M1 in Rel. Coulex*

N. Shimizu	Tokyo
T. Suzuki	Nihon U.
Y. Utsuno	JAEA
M. Honma	Aizu
N. Tsunoda	(Tokyo)
K. Tsukiyama	(Tokyo)
M. H.-Jensen	Oslo/MSU
A. Schwenk	Darmstadt
J. Holt	Darmstadt
K. Akaishi	RIKEN
Y. Tsunoda	Tokyo
T. Mizusaki	Senshu U.
B.A. Brown	MSU