Shell model calculations for exotic nuclei with realistic potentials: reliability and predictiveness

Luigi Coraggio

Istituto Nazionale di Fisica Nucleare - Sezione di Napoli

NUSPIN 2017
June 28th, 2017 - GSI, Darmstadt

- A. Covello (UNINA and INFN)
- A. Gargano (INFN)
- N. Itaco (UNINA2 and INFN)
- T. T. S. Kuo (SUNY at Stony Brook, USA)
- L. C. (INFN)

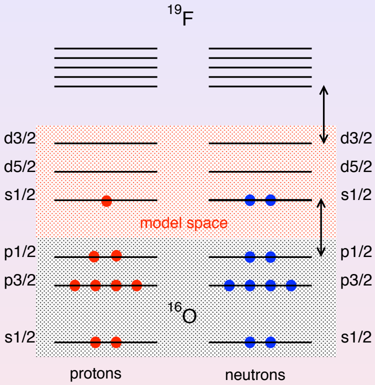
Part I

The theoretical framework

Introductory remark

What is a realistic effective shell-model hamiltonian ?

An example: ^{19}F



- 9 protons & 10 neutrons interacting
- spherically symmetric mean field (e.g. harmonic oscillator)
- 1 valence proton & 2 valence neutrons interacting in a truncated model space

The degrees of freedom of the core nucleons and the excitations of the valence ones above the model space are not considered explicitly.

Effective shell-model hamiltonian

The shell-model hamiltonian has to take into account in an effective way all the degrees of freedom not explicitly considered

Two alternative approaches

- phenomenological
- microscopic

$V_{NN} \ \ (+V_{NNN}) \Rightarrow$ many-body theory $\Rightarrow H_{\rm eff}$

Definition

The eigenvalues of $H_{\rm eff}$ belong to the set of eigenvalues of the full nuclear hamiltonian

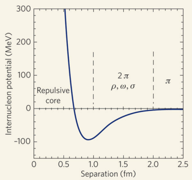
Workflow for a realistic shell-model calculation

1. Choose a realistic *NN* potential (*NNN*)
2. Determine the model space better tailored to study the system under investigation
3. Derive the effective shell-model hamiltonian by way of the many-body theory
4. Calculate the physical observables (energies, e.m. transition probabilities, ...)

Realistic nucleon-nucleon potential: V_{NN}

Several realistic potentials $\chi^2/datum \simeq 1$:
CD-Bonn, Argonne V18, Nijmegen, ...

Strong short-range repulsion



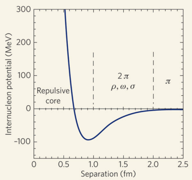
How to handle the short-range repulsion ?

- Brueckner *G* matrix
- EFT inspired approaches
  - $V_{\mathrm{low-k}}$
  - SRG
  - chiral potentials

Realistic nucleon-nucleon potential: V_{NN}

Several realistic potentials $\chi^2/datum \simeq 1$:
CD-Bonn, Argonne V18, Nijmegen, ...

Strong short-range repulsion

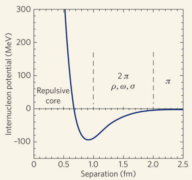


How to handle the short-range repulsion ?

- Brueckner *G* matrix
- EFT inspired approaches
  - $V_{\rm low-k}$
  - SRG
  - chiral potentials

Realistic nucleon-nucleon potential: V_{NN}

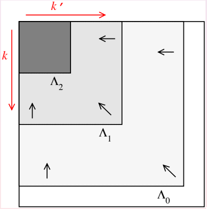
Strong short-range repulsion



Several realistic potentials $\chi^2/\mathit{datum} \simeq 1$:
CD-Bonn, Argonne V18, Nijmegen, ...

How to handle the short-range repulsion ?

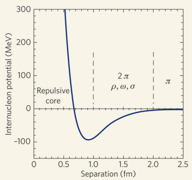
- Bruckner *G* matrix
- EFT inspired approaches
  - $V_{\rm low-k}$
  - SRG
  - chiral potentials



Realistic nucleon-nucleon potential: V_{NN}

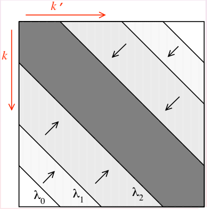
Several realistic potentials $\chi^2/datum \simeq 1$:
CD-Bonn, Argonne V18, Nijmegen, ...

Strong short-range repulsion



How to handle the short-range repulsion ?

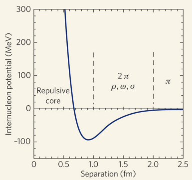
- Brueckner *G* matrix
- EFT inspired approaches
    - $V_{\rm low-k}$
    - SRG
    - chiral potentials



Realistic nucleon-nucleon potential: V_{NN}

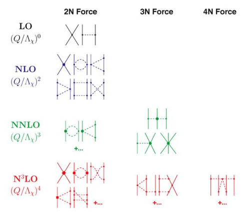
Several realistic potentials $\chi^2/datum \simeq 1$:
CD-Bonn, Argonne V18, Nijmegen, ...

Strong short-range repulsion



How to handle the short-range repulsion ?

- Brueckner *G* matrix
- EFT inspired approaches
  - $V_{\mathrm{low-k}}$
  - SRG
  - chiral potentials



The shell-model effective hamiltonian

A-nucleon system Schrödinger equation

$$H|\Psi_\nu\rangle = E_\nu|\Psi_\nu\rangle$$

with

$$H = H_0 + H_1 = \sum_{i=1}^{A}(T_i + U_i) + \sum_{i<j}(V_{ij}^{NN} - U_i)$$

Model space

$$|\Phi_i\rangle = [a_1^\dagger a_2^\dagger \ldots a_n^\dagger]_i|c\rangle \Rightarrow P = \sum_{i=1}^{d}|\Phi_i\rangle\langle\Phi_i|$$

Model-space eigenvalue problem

$$H_{\mathrm{eff}}P|\Psi_\alpha\rangle = E_\alpha P|\Psi_\alpha\rangle$$

The shell-model effective hamiltonian

$$\left(\begin{array}{c|c} PHP & PHQ \\ \hline QHP & QHQ \end{array}\right) \overset{\mathcal{H}=X^{-1}HX}{\underset{Q\mathcal{H}P=0}{\Longrightarrow}} \left(\begin{array}{c|c} P\mathcal{H}P & P\mathcal{H}Q \\ \hline 0 & Q\mathcal{H}Q \end{array}\right)$$

$$H_{\rm eff} = P\mathcal{H}P$$

Suzuki & Lee $\Rightarrow X = e^{\omega}$ with $\omega = \left(\begin{array}{c|c} 0 & 0 \\ \hline Q\omega P & 0 \end{array}\right)$

$$H_1^{\rm eff}(\omega) = PH_1P + PH_1Q\frac{1}{\epsilon - QHQ}QH_1P -$$
$$-PH_1Q\frac{1}{\epsilon - QHQ}\omega H_1^{\rm eff}(\omega)$$

The shell-model effective hamiltonian

Folded-diagram expansion

$\hat{Q}$-box vertex function

$$\hat{Q}(\epsilon) = PH_1P + PH_1Q\frac{1}{\epsilon - QHQ}QH_1P$$

$\Rightarrow$ Recursive equation for $H_{\rm eff}$ $\Rightarrow$ iterative techniques (Krenciglowa-Kuo, Lee-Suzuki, ...)

$$H_{\rm eff} = \hat{Q} - \hat{Q}' \int \hat{Q} + \hat{Q}' \int \hat{Q} \int \hat{Q} - \hat{Q}' \int \hat{Q} \int \hat{Q} \int \hat{Q} \cdots ,$$

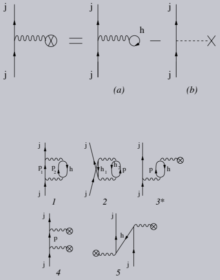
The perturbative approach to the shell-model $H^{\rm eff}$

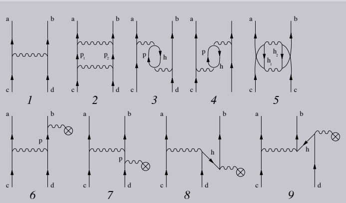
$$\hat{Q}(\epsilon) = PH_1P + PH_1Q\frac{1}{\epsilon - QHQ}QH_1P$$

The $\hat{Q}$-box can be calculated perturbatively

$$\frac{1}{\epsilon - QHQ} = \sum_{n=0}^{\infty} \frac{(QH_1Q)^n}{(\epsilon - QH_0Q)^{n+1}}$$

The diagrammatic expansion of the $\hat{Q}$-box





The shell-model effective operators

Consistently, any shell-model effective operator may be calculated

It has been demonstrated that, for any bare operator Θ, a non-Hermitian effective operator $\Theta_{\rm eff}$ can be written in the following form:

$$\begin{aligned} \Theta_{\rm eff} &= (P + \hat{Q}_1 + \hat{Q}_1 \hat{Q}_1 + \hat{Q}_2 \hat{Q} + \hat{Q} \hat{Q}_2 + \cdots)(\chi_0 + \\ &+ \chi_1 + \chi_2 + \cdots) \ , \end{aligned}$$

where

$$\hat{Q}_m = \frac{1}{m!} \frac{d^m \hat{Q}(\epsilon)}{d\epsilon^m} \bigg|_{\epsilon=\epsilon_0} \ ,$$

ϵ_0 being the model-space eigenvalue of the unperturbed hamiltonian H_0

K. Suzuki and R. Okamoto, Prog. Theor. Phys. ***93*** *, 905 (1995)*

The shell-model effective operators

The χ_n operators are defined as follows:

$$\begin{aligned}
\chi_0 &= (\hat{\Theta}_0 + h.c.) + \Theta_{00} \quad , \\
\chi_1 &= (\hat{\Theta}_1 \hat{Q} + h.c.) + (\hat{\Theta}_{01} \hat{Q} + h.c.) \quad , \\
\chi_2 &= (\hat{\Theta}_1 \hat{Q}_1 \hat{Q} + h.c.) + (\hat{\Theta}_2 \hat{Q} \hat{Q} + h.c.) + \\
& \quad (\hat{\Theta}_{02} \hat{Q} \hat{Q} + h.c.) + \hat{Q} \hat{\Theta}_{11} \hat{Q} \quad , \\
& \quad \ldots
\end{aligned}$$

and

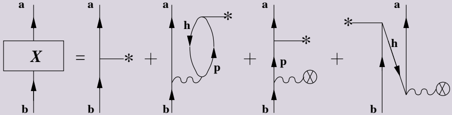
$$\begin{aligned}
\hat{\Theta}(\epsilon) &= P \Theta P + P \Theta Q \frac{1}{\epsilon - QHQ} Q H_1 P \quad , \\
\hat{\Theta}(\epsilon_1 ; \epsilon_2) &= P \Theta P + P H_1 Q \frac{1}{\epsilon_1 - QHQ} \times \\
& \quad Q \Theta Q \frac{1}{\epsilon_2 - QHQ} Q H_1 P \quad ,
\end{aligned}$$

$$\hat{\Theta}_m = \frac{1}{m!} \frac{d^m \hat{\Theta}(\epsilon)}{d\epsilon^m} \bigg|_{\epsilon=\epsilon_0} \quad , \quad \hat{\Theta}_{nm} = \frac{1}{n! m!} \frac{d^n}{d\epsilon_1^n} \frac{d^m}{d\epsilon_2^m} \hat{\Theta}(\epsilon_1 ; \epsilon_2) \bigg|_{\epsilon_1=\epsilon_0, \epsilon_2=\epsilon_0}$$

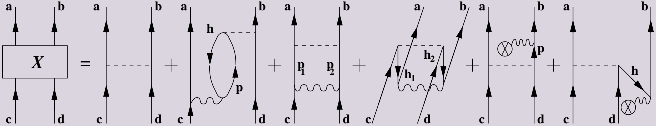
The shell-model effective operators

We arrest the χ series at χ_0, and expand it perturbatively:

One-body operator

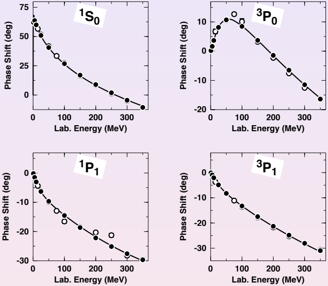


Two-body operator



Our recipe for realistic shell model

- Input V_{NN}: $V_{\rm low-k}$ derived from the high-precision *NN* CD-Bonn potential with a cutoff: $\Lambda = 2.6$ fm^{-1}.



- $H_{\rm eff}$ obtained calculating the Q-box up to the 3rd order in perturbation theory.
- Effective operators are consistently derived by way of the the MBPT

Part II

Reliability

Large-scale realistic shell-model calculations

Neutron-rich isotopic chains

Approaching neutron drip line:

Shell-model study of the onset of collectivity at $N = 40$

L.C., A. Covello, A. Gargano, and N. Itaco, Phys. Rev. C **89**, *024319 (2014)*

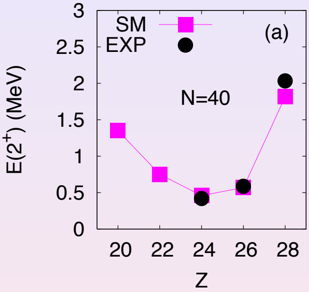
Proton-rich isotopic chains

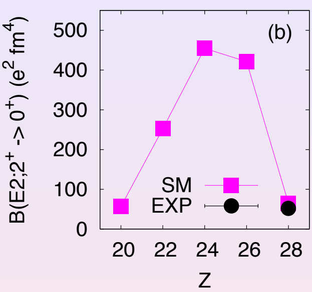
Approaching proton drip line:

Enhanced quadrupole collectivity of neutron-deficient tin isotopes

L.C., A. Covello, A. Gargano, N. Itaco, and T. T. S. Kuo, Phys. Rev. C **91**, *041301 (2015)*

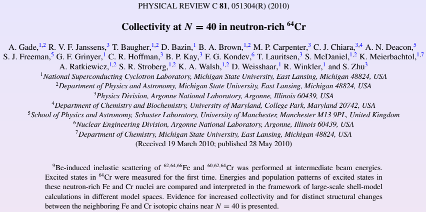
Collectivity at $N = 40$





⇒ shell-model study of neutron-rich isotopic chains outside ^{48}Ca
⇒ Collective behavior framed within the quasi-SU(3) approximate symmetry
⇒ Two model spaces with ^{48}Ca inert core, including or not the neutron $1d_{5/2}$ orbital

The collectivity at $N = 40$



PHYSICAL REVIEW C **81**, 051304(R) (2010)

Collectivity at $N = 40$ in neutron-rich ^{64}Cr

A. Gade,[1,2] R. V. F. Janssens,[3] T. Baugher,[1,2] D. Bazin,[1] B. A. Brown,[1,2] M. P. Carpenter,[3] C. J. Chiara,[3,4] A. N. Deacon,[5]
S. J. Freeman,[5] G. F. Grinyer,[1] C. R. Hoffman,[3] B. P. Kay,[3] F. G. Kondev,[6] T. Lauritsen,[3] S. McDaniel,[1,2] K. Meierbachtol,[1,7]
A. Ratkiewicz,[1,2] S. R. Stroberg,[1,2] K. A. Walsh,[1,2] D. Weisshaar,[1] R. Winkler,[1] and S. Zhu[3]
[1] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[2] *Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[3] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[4] *Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA*
[5] *School of Physics and Astronomy, Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom*
[6] *Nuclear Engineering Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[7] *Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
(Received 19 March 2010; published 28 May 2010)

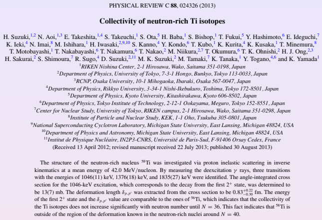
^{9}Be-induced inelastic scattering of ^{62,64,66}Fe and ^{60,62,64}Cr was performed at intermediate beam energies. Excited states in ^{64}Cr were measured for the first time. Energies and population patterns of excited states in these neutron-rich Fe and Cr nuclei are compared and interpreted in the framework of large-scale shell-model calculations in different model spaces. Evidence for increased collectivity and for distinct structural changes between the neighboring Fe and Cr isotopic chains near $N = 40$ is presented.

PHYSICAL REVIEW C **81**, 061301(R) (2010)

Onset of collectivity in neutron-rich Fe isotopes: Toward a new island of inversion?

J. Ljungvall,[1,2,3] A. Görgen,[1] A. Obertelli,[1] W. Korten,[1] E. Clément,[2] G. de France,[2] A. Bürger,[4] J.-P. Delaroche,[5] A. Dewald,[6]
A. Gadea,[7] L. Gaudefroy,[5] M. Girod,[5] M. Hackstein,[6] J. Libert,[8] D. Mengoni,[9] F. Nowacki,[10] T. Pissulla,[6] A. Poves,[11]
F. Recchia,[12] M. Rejmund,[2] W. Rother,[6] E. Sahin,[12] C. Schmitt,[2] A. Shrivastava,[2] K. Sieja,[10] J. J. Valiente-Dobón,[12]
K. O. Zell,[6] and M. Zielińska[13]
[1] *CEA Saclay, IRFU, Service de Physique Nucléaire, F-91191 Gif-sur-Yvette, France*
[2] *GANIL, CEA/DSM-CNRS/IN2P3, Bd Henri Becquerel, BP 55027, F-14076 Caen, France*
[3] *CSNSM, CNRS/IN2P3, F-91405 Orsay, France*
[4] *Department of Physics, University of Oslo, PO Box 1048 Blindern, N-0316 Oslo, Norway*
[5] *CEA, DAM, DIF, F-91297 Arpajon, France*
[6] *Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany*
[7] *Instituto de Fisica Corpuscular, CSIC-Universidad de Valencia, E-46071 Valencia, Spain*
[8] *Institut de Physique Nucléaire, CNRS/IN2P3-Université Paris-Sud, F-91406 Orsay, France*
[9] *Dipartimento di Fisica dell'Università and INFN Sezione di Padova, I-35131 Padova, Italy*
[10] *IPHC, CNRS/IN2P3 and Université Louis Pasteur, F-67037 Strasbourg, France*
[11] *Departamento de Física Teórica, IFT-AM/CSIC, Universidad Autónoma, E-28049 Madrid, Spain*
[12] *INFN, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy*
[13] *Heavy Ion Laboratory, Warsaw University, Warsaw, PL-02097, Poland*
(Received 8 March 2010; published 15 June 2010)

The lifetimes of the first excited 2^+ states in ^{62}Fe and ^{64}Fe have been measured for the first time using the recoil-distance Doppler shift method after multinucleon transfer reactions in inverse kinematics. A sudden increase of collectivity from ^{62}Fe to ^{64}Fe is observed. The experimental results are compared with new large-scale shell-model calculations and Hartree-Fock-Bogolyubov–based configuration-mixing calculations using the Gogny D1S interaction. The results give a deeper understanding of the mechanism leading to an onset of collectivity near ^{68}Ni, which is compared with the situation in the so-called *island of inversion* around ^{32}Mg.

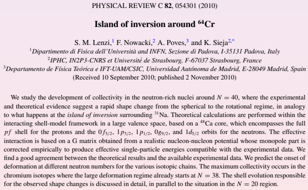


PHYSICAL REVIEW C **88**, 024326 (2013)

Collectivity of neutron-rich Ti isotopes

H. Suzuki,[1,2] N. Aoi,[1,3] E. Takeshita,[1,4] S. Takeuchi,[1] S. Ota,[5] H. Baba,[1] S. Bishop,[1] T. Fukui,[5] Y. Hashimoto,[6] E. Ideguchi,[7]
K. Ieki,[4] N. Imai,[8] M. Ishihara,[1] H. Iwasaki,[2,9,10] S. Kanno,[4] Y. Kondo,[6] T. Kubo,[1] K. Kurita,[4] K. Kusaka,[1] T. Minemura,[8]
T. Motobayashi,[1] T. Nakabayashi,[6] T. Nakamura,[6] T. Nakao,[2] M. Niikura,[2,7] T. Okumura,[6] T. K. Ohnishi,[2] H. J. Ong,[2,3]
H. Sakurai,[2] S. Shimoura,[7] R. Sugo,[4] D. Suzuki,[2,11] M. K. Suzuki,[2] M. Tamaki,[7] K. Tanaka,[1] Y. Togano,[4,6] and K. Yamada[1]
[1] *RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[2] *Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan*
[3] *RCNP, Osaka University, 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan*
[4] *Department of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 172-8501, Japan*
[5] *Department of Physics, Kyoto University, Kitashirakawa, Kyoto 606-8502, Japan*
[6] *Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo 152-8551, Japan*
[7] *Center for Nuclear Study, University of Tokyo, RIKEN campus, 2-1 Hirosawa, Wako, Saitama 351-0298, Japan*
[8] *Institute of Particle and Nuclear Study, KEK, 1-1 Oho, Tsukuba 305-0801, Japan*
[9] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[10] *Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[11] *Institut de Physique Nucléaire, IN2P3-CNRS, Université de Paris-Sud, F-91406 Orsay Cedex, France*
(Received 13 April 2012; revised manuscript received 22 July 2013; published 30 August 2013)

The structure of the neutron-rich nucleus ^{58}Ti was investigated via proton inelastic scattering in inverse kinematics at a mean energy of 42.0 MeV/nucleon. By measuring the deexcitation γ rays, three transitions with the energies of 1046(11) keV, 1376(18) keV, and 1835(27) keV were identified. The angle-integrated cross section for the 1046-keV excitation, which corresponds to the decay from the first 2^+ state, was determined to be 13(7) mb. The deformation length $\delta_{p,p'}$ was extracted from the cross section to be $0.83^{+0.22}_{-0.30}$ fm. The energy of the first 2^+ state and the $\delta_{p,p'}$ value are comparable to the ones of ^{56}Ti, which indicates that the collectivity of the Ti isotopes does not increase significantly with neutron number until $N = 36$. This fact indicates that ^{58}Ti is outside of the region of the deformation known in the neutron-rich nuclei around $N = 40$.



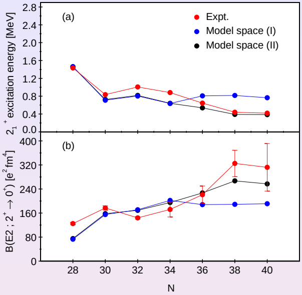
PHYSICAL REVIEW C **82**, 054301 (2010)

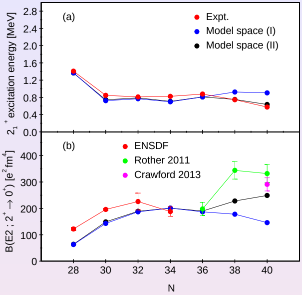
Island of inversion around ^{64}Cr

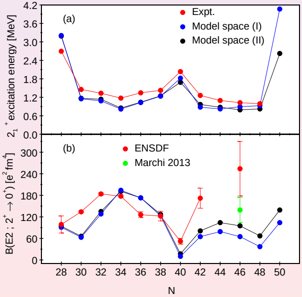
S. M. Lenzi,[1] F. Nowacki,[2] A. Poves,[3] and K. Sieja[2,*]
[1] *Dipartimento di Fisica dell'Università and INFN, Sezione di Padova, I-35131 Padova, Italy*
[2] *IPHC, IN2P3-CNRS et Université de Strasbourg, F-67037 Strasbourg, France*
[3] *Departamento de Física Teórica e IFT-UAM/CSIC, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*
(Received 10 September 2010; published 2 November 2010)

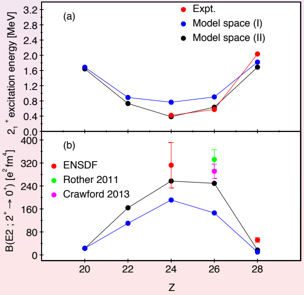
We study the development of collectivity in the neutron-rich nuclei around $N = 40$, where the experimental and theoretical evidence suggest a rapid shape change from the spherical to the rotational regime, in analogy to what happens at the *island of inversion* surrounding ^{31}Na. Theoretical calculations are performed within the interacting shell-model framework in a large valence space, based on a ^{48}Ca core, which encompasses the full pf shell for the protons and the $0f_{5/2}$, $1p_{3/2}$, $1p_{1/2}$, $0g_{9/2}$, and $1d_{5/2}$ orbits for the neutrons. The effective interaction is based on a G matrix obtained from a realistic nucleon-nucleon potential whose monopole part is corrected empirically to produce effective single-particle energies compatible with the experimental data. We find a good agreement between the theoretical results and the available experimental data. We predict the onset of deformation at different neutron numbers for the various isotopic chains. The maximum collectivity occurs in the chromium isotopes where the large deformation regime already starts at $N = 38$. The shell evolution responsible for the observed shape changes is discussed in detail, in parallel to the situation in the $N = 20$ region.

Collectivity at $N = 40$

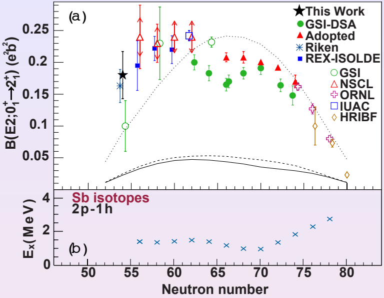








Enhanced quadrupole collectivity in light tin isotopes



⇒ shell-model study of neutron-deficient tin isotopes using ^{88}Sr as a core

⇒ Quadrupole collectivity enhanced by the $Z = 50$ cross-shell excitations

⇒ Model space spanned by proton $1p_{1/2}, 0g_{9/2}, 0g_{7/2}, 1d_{5/2}$ and $0g_{7/2}, 1d_{5/2}$ orbitals

⇒ Theoretical single-particle energies, two-body matrix elements, and effective charges have been employed

Calculation of the effective charges

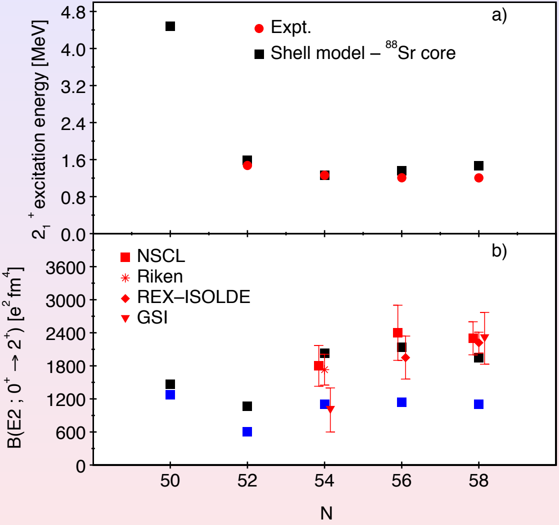
Proton effective charges

$n_a l_a j_a$	$n_b l_b j_b$	$\langle a \| e_p \| b \rangle$
$0g_{9/2}$	$0g_{9/2}$	1.62
$0g_{9/2}$	$0g_{7/2}$	1.67
$0g_{9/2}$	$1d_{5/2}$	1.60
$0g_{7/2}$	$0g_{7/2}$	1.73
$0g_{7/2}$	$1d_{5/2}$	1.74
$0g_{7/2}$	$1d_{3/2}$	1.76
$1d_{5/2}$	$1d_{5/2}$	1.73
$1d_{5/2}$	$1d_{3/2}$	1.72
$1d_{5/2}$	$2s_{1/2}$	1.76
$1d_{3/2}$	$1d_{3/2}$	1.74
$1d_{3/2}$	$2s_{1/2}$	1.76
$0h_{11/2}$	$0h_{11/2}$	1.72

Neutron effective charges

$n_a l_a j_a$	$n_b l_b j_b$	$\langle a \| e_n \| b \rangle$
$0g_{7/2}$	$0g_{7/2}$	0.94
$0g_{7/2}$	$1d_{5/2}$	0.96
$0g_{7/2}$	$1d_{3/2}$	0.95
$1d_{5/2}$	$1d_{5/2}$	0.94
$1d_{5/2}$	$1d_{3/2}$	0.97
$1d_{5/2}$	$2s_{1/2}$	0.79
$1d_{3/2}$	$1d_{3/2}$	0.96
$1d_{3/2}$	$2s_{1/2}$	0.79
$0h_{11/2}$	$0h_{11/2}$	0.87

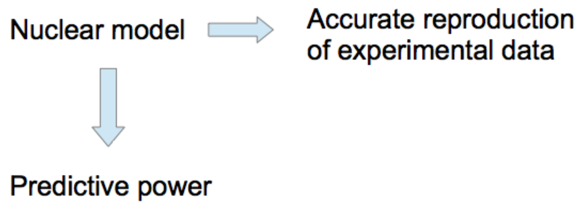
Enhanced quadrupole collectivity in light tin isotopes



Part III

Predictiveness

Nuclear models and predictive power

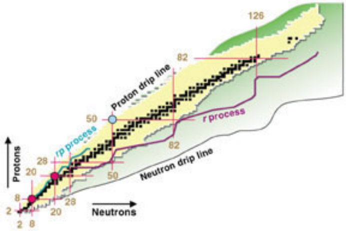


Nuclear model

Accurate reproduction of experimental data

Predictive power

RIBs & advances in detection techniques ⇒ unknown structure of nuclei towards the drip lines



Realistic shell-model calculations

realistic shell-model calculations in different mass regions

⇓

results in good agreement with experimental data

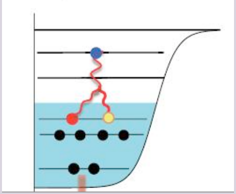
Can realistic shell-model calculations be predictive ?

few selected examples

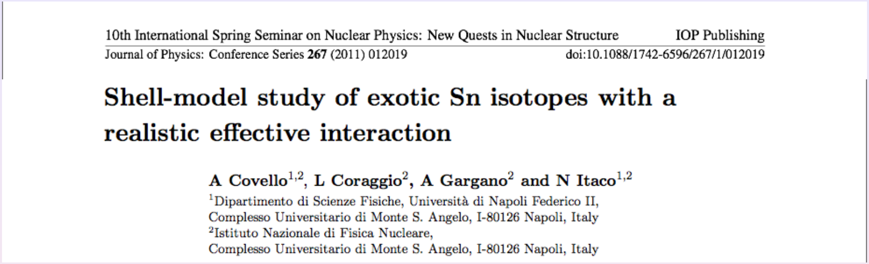
Few selected physics cases

- Sn isotopes beyond $N = 82$
- heavy calcium isotopes
- neutron-rich titanium and nickel isotopes

Single-particle energies from the experiment $\Rightarrow$ reduced role of $3N$ force



Sn isotopes beyond $N = 82$



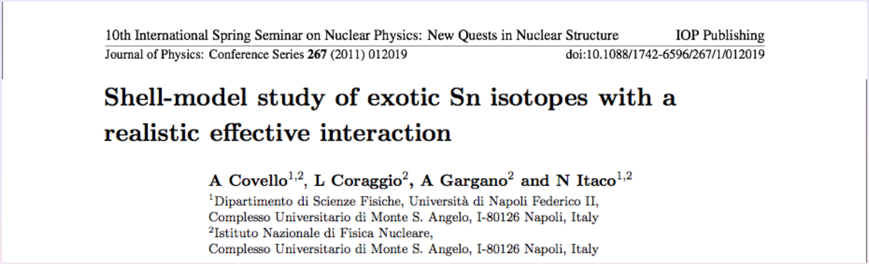
10th International Spring Seminar on Nuclear Physics: New Quests in Nuclear Structure IOP Publishing
Journal of Physics: Conference Series **267** (2011) 012019 doi:10.1088/1742-6596/267/1/012019

Shell-model study of exotic Sn isotopes with a realistic effective interaction

A Covello[1,2], L Coraggio[2], A Gargano[2] and N Itaco[1,2]
[1]Dipartimento di Scienze Fisiche, Università di Napoli Federico II,
Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
[2]Istituto Nazionale di Fisica Nucleare,
Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy

- $\Rightarrow$ shell-model study of Sn isotopes beyond N = 82
- $\Rightarrow$ $V_{\mathrm{low-k}}$ from CD-Bonn *NN* potential
- $\Rightarrow$ $h_{9/2}fpi_{13/2}$ model space with ^{132}Sn inert core
- $\Rightarrow$ SP energies from ^{133}Sn

Sn isotopes beyond $N = 82$



10th International Spring Seminar on Nuclear Physics: New Quests in Nuclear Structure IOP Publishing
Journal of Physics: Conference Series **267** (2011) 012019 doi:10.1088/1742-6596/267/1/012019

Shell-model study of exotic Sn isotopes with a realistic effective interaction

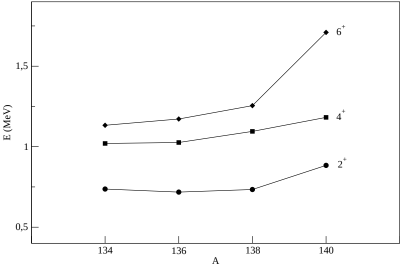
A Covello[1,2], L Coraggio[2], A Gargano[2] and N Itaco[1,2]
[1]Dipartimento di Scienze Fisiche, Università di Napoli Federico II,
Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
[2]Istituto Nazionale di Fisica Nucleare,
Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy

⇒ shell-model study of Sn isotopes beyond N = 82

... It is the aim of our study to compare the results of our calculations with the available experimental data and to make predictions for the neighboring heavier isotopes ...

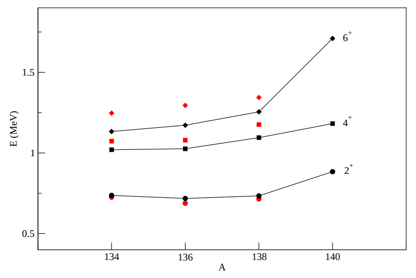
Sn isotopes beyond $N = 82$

Excitation energies of the 2_1^+, 4_1^+, and 6_1^+ states in Sn isotopes



Sn isotopes beyond $N = 82$

Excitation energies of the 2_1^+, 4_1^+, and 6_1^+ states in Sn isotopes

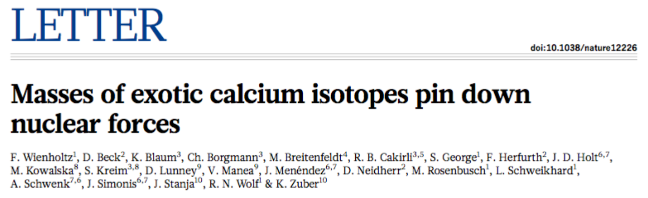



PRL **113,** 132502 (2014) PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 2014

Yrast 6^+ Seniority Isomers of ^{136,138}Sn

G. S. Simpson,[1,2,3] G. Gey,[3,4,5] A. Jungclaus,[6] J. Taprogge,[6,7,5] S. Nishimura,[5] K. Sieja,[8] P. Doornenbal,[5] G. Lorusso,[5] P.-A. Söderström,[5] T. Sumikama,[9] Z. Y. Xu,[10] H. Baba,[5] F. Browne,[11,5] N. Fukuda,[5] N. Inabe,[5] T. Isobe,[5] H. S. Jung,[12,*] D. Kameda,[5] G. D. Kim,[13] Y.-K. Kim,[13,14] I. Kojouharov,[15] T. Kubo,[5] N. Kurz,[15] Y. K. Kwon,[13] Z. Li,[16] H. Sakurai,[5,10]

Heavy calcium isotopes



LETTER

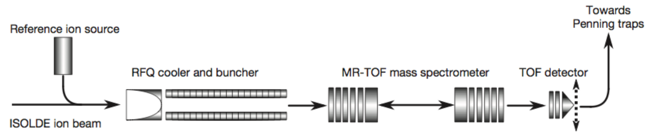
doi:10.1038/nature12226

Masses of exotic calcium isotopes pin down nuclear forces

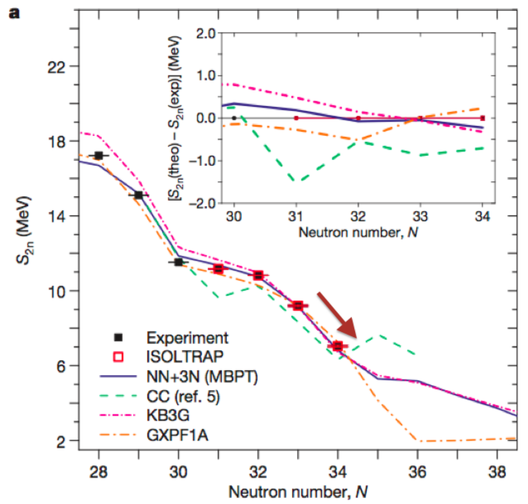
F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6,7], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[7,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

⇒ first mass measurements of ^{53}Ca and ^{54}Ca

⇒ new method of precision mass spectroscopy with ISOLTRAP

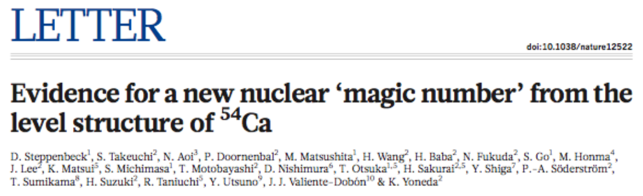


Heavy calcium isotopes



" ... pronounced decrease in S_{2n} revealed by the new ^{53}Ca and ^{54}Ca ISOLTRAP masses ..."

Heavy calcium isotopes



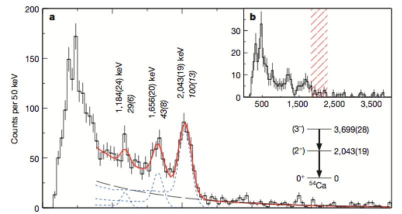
LETTER

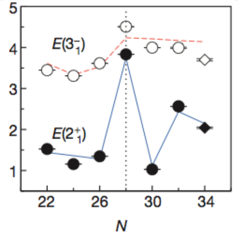
doi:10.1038/nature12522

Evidence for a new nuclear ‘magic number’ from the level structure of ^{54}Ca

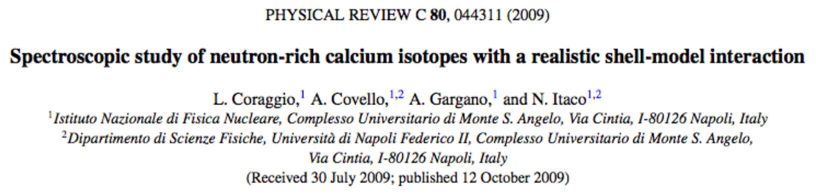
D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

- ⇒ spectroscopic study of ^{54}Ca
- ⇒ proton knockout reactions involving ^{55}Sc and ^{56}Ti projectiles





Heavy calcium isotopes



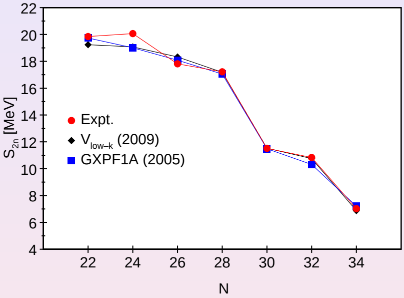
PHYSICAL REVIEW C **80**, 044311 (2009)

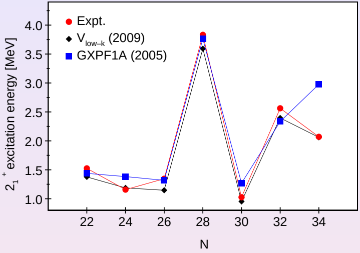
Spectroscopic study of neutron-rich calcium isotopes with a realistic shell-model interaction

L. Coraggio,[1] A. Covello,[1,2] A. Gargano,[1] and N. Itaco[1,2]
[1]*Istituto Nazionale di Fisica Nucleare, Complesso Universitario di Monte S. Angelo, Via Cintia, I-80126 Napoli, Italy*
[2]*Dipartimento di Scienze Fisiche, Università di Napoli Federico II, Complesso Universitario di Monte S. Angelo,*
Via Cintia, I-80126 Napoli, Italy
(Received 30 July 2009; published 12 October 2009)

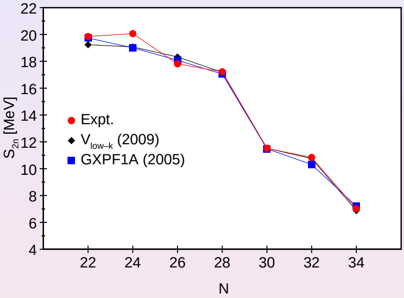
$\Rightarrow$ shell-model study of neutron-rich calcium isotopes
$\Rightarrow$ *fp* model space with ^{40}Ca inert core
$\Rightarrow$ predictions for the (at that time) unknown spectra of $^{53-56}$Ca

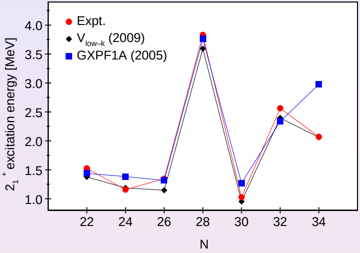
Heavy calcium isotopes: shell-model results



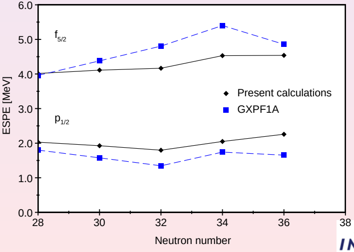


Heavy calcium isotopes: shell-model results

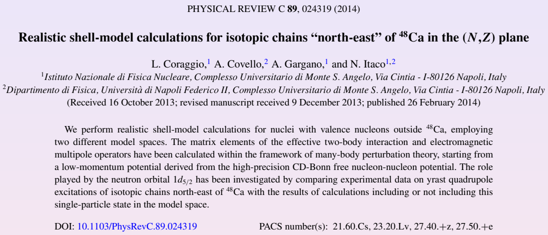




different monopole properties



Isotopic chains “north-east” of ^{48}Ca



PHYSICAL REVIEW C **89**, 024319 (2014)

Realistic shell-model calculations for isotopic chains “north-east” of ^{48}Ca in the (N,Z) plane

L. Coraggio,[1] A. Covello,[2] A. Gargano,[1] and N. Itaco[1,2]
[1]*Istituto Nazionale di Fisica Nucleare, Complesso Universitario di Monte S. Angelo, Via Cintia - I-80126 Napoli, Italy*
[2]*Dipartimento di Fisica, Università di Napoli Federico II, Complesso Universitario di Monte S. Angelo, Via Cintia - I-80126 Napoli, Italy*

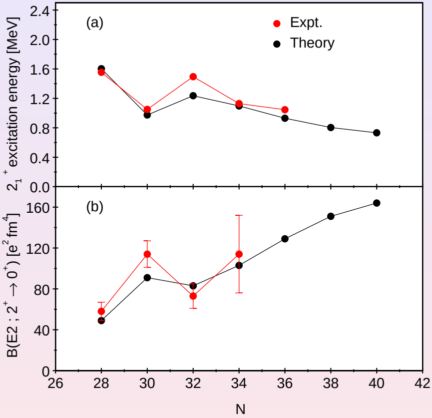
(Received 16 October 2013; revised manuscript received 9 December 2013; published 26 February 2014)

We perform realistic shell-model calculations for nuclei with valence nucleons outside ^{48}Ca, employing two different model spaces. The matrix elements of the effective two-body interaction and electromagnetic multipole operators have been calculated within the framework of many-body perturbation theory, starting from a low-momentum potential derived from the high-precision CD-Bonn free nucleon-nucleon potential. The role played by the neutron orbital $1d_{5/2}$ has been investigated by comparing experimental data on yrast quadrupole excitations of isotopic chains north-east of ^{48}Ca with the results of calculations including or not including this single-particle state in the model space.

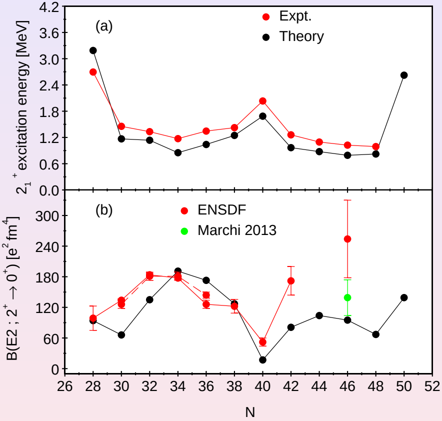
DOI: 10.1103/PhysRevC.89.024319 PACS number(s): 21.60.Cs, 23.20.Lv, 27.40.+z, 27.50.+e

⇒ shell-model study of neutron-rich isotopic chains outside ^{48}Ca
⇒ *fpgd* model space with ^{48}Ca inert core
⇒ predictions for the (at that time) unknown spectra exotic Ti isotopes and of ^{78}Ni shell closure

Isotopic chains “north-east” of ^{48}Ca: shell-model results

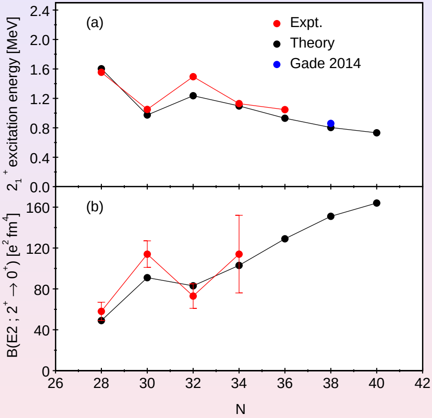


Titanium isotopes

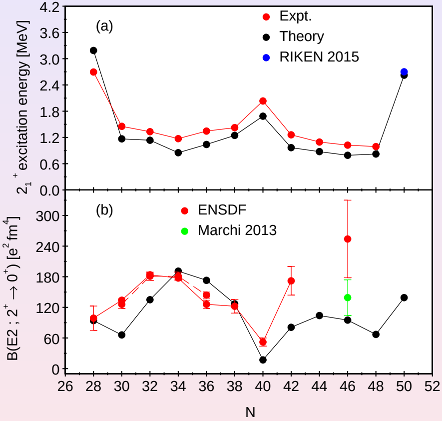


Nickel isotopes

Isotopic chains “north-east” of ^{48}Ca: shell-model results



Titanium isotopes

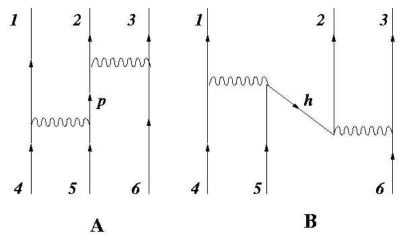


Nickel isotopes

Conclusions and outlook

- The agreement of our results with the experimental data testifies the reliability of a microscopic shell-model calculation with realistic potentials.
- We have now evidence of the predictive power of realistic shell model
- Role of real three-body forces and three-body correlations should be investigated.

- Perspectives: benchmark calculations with other many-body approaches.



These terms introduce density dependence into the effective shell-model hamiltonian

Conclusions and outlook

- The agreement of our results with the experimental data testifies the reliability of a microscopic shell-model calculation with realistic potentials.
- We have now evidence of the predictive power of realistic shell model
- Role of real three-body forces and three-body correlations should be investigated.
- Perspectives: benchmark calculations with other many-body approaches.