Single-particle states around ^{132}Sn by realistic shell-model calculations

Angela Gargano, INFN Napoli

Shell Model as a Unfied View of Nucler Structure

Workshop in honor of founders of Strasbourg-Madrid Shell Model Collaboration: E. Caurier, A. Poves and A. P. Zuker

Strasbourg, October 8-10, 2012

^{133}Sn	^{135}Te	^{137}Xe

Evolution of the single-neutron states in the N=82-126 shell

Z	N=83		
	50	52	54

^{133}Sb	^{135}Sb	^{137}Sb

Evolution of the single-proton states in the Z=50-82 shell

N	Z=51		
	82	84	86

Outline

- **Theoretical framework**
- **Physics case:**
  - **Motivation**
  - **Discussion of the results and comparison with experiment**
- **Conclusions**

Shell-model Hamiltonian

$$H = \sum_i \varepsilon_i a_i^+ a_i + \frac{1}{4} \sum_{ijkl} \langle ij | V_{eff} | kl \rangle a_i^+ a_j^+ a_l a_k$$

defined within a reduced model space and acting only between valence nucleons

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has to take into account *in an effective way* all the degrees of freedom not explicitly considered:

- configurations beyond the chosen model space
- core polarization effects

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Alternative approaches

- phenomenological
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- Understand the properties of nuclei starting from the forces between nucleons

- No adjustable parameters

Derivation of H_{eff}

Two main ingredients

- Nucleon-Nucleon potential
- Many-body perturbative theory

L. Coraggio et al, Prog. Part. Nucl. Phys. 62, 135 (2009)
L. Coraggio et al, Annals of Phys. 327, 2061 (2012)

Nucleon-nucleon potential

Potentials which reproduce the two-body experimental data (deuteron properties and the NN scattering data up the inelastic threshold) with

$\chi^2/N_{data} \sim 1$

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- Nijmegen II
- CD-Bonn
- Argonne V_{18}
- Chiral potentials

Problem:

these potentials have a strongly repulsive short-range component

↓

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Remedy:

V_{low-k} approach

construction of a *NN* potential confined within a

low- momentum space

by integrating out the high-momentum components of V_{NN} down to a momentum-space cutoff Λ

V_{low-k} preserves the physics of the original NN potential

Realistic shell-model calculation

Schrödinger equation for A nucleons

$$H\psi_i = (H_0 + H_1)\psi_i = E_i\psi_i$$

$$\begin{cases} H_0 = T + U \\ H_1 = V_{NN} - U \end{cases}$$

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Shell-model equation for N-valence nucleons

$$PH_{eff}P\psi_i = P(H_0 + V_{eff})P\psi_i = E_iP\psi_i$$

P - projection operator onto the chosen model space defined in terms of H_0 eigenvectors

$\hat{Q}$ - box folded-diagram method

- V_{eff} is written as recursive equation

in terms of the $\hat{Q}$ - box and its derivatives

$$\hat{Q} = PH_1P + PH_1Q \frac{1}{\varepsilon - QHQ} QH_1P$$

Q=1-P

ε = unperturbed energy for a degenerate model space

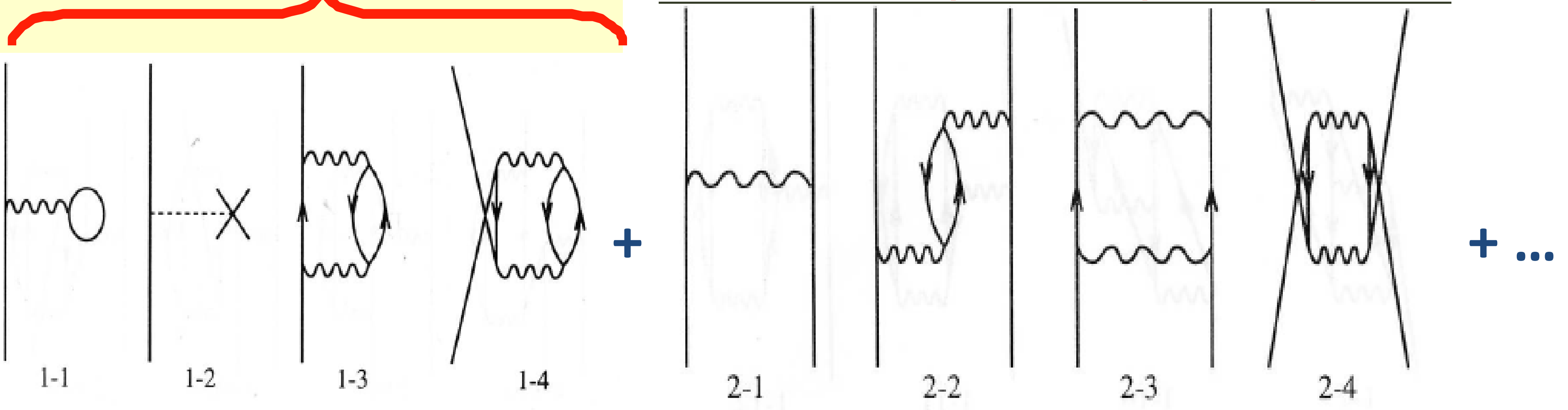
$$PH_0P = \varepsilon P$$

- V_{eff} solved by iterative techniques (Krenciglowa-Kuo, Lee-Suzuki)

Diagrammatic expansion of the $\hat{Q}$ - box

1-body diagrams up to 2nd order **S-box**

2-body diagrams up to 2nd order: V V_{1p1h} V_{2p} V_{2p2h}



with V_{low-k} in the interaction vertices

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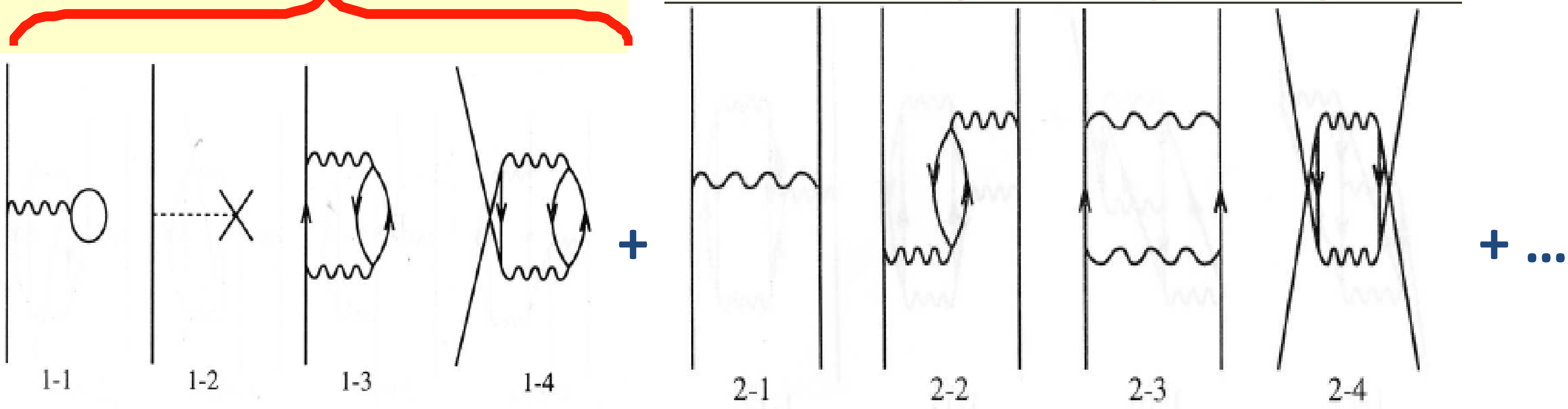

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Calculation:

- inclusion of diagrams up to finite order in the interaction
- truncation of the intermediate-state summation

Remarks on the calculation of V_{eff}

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◆ V_{eff} is constructed for a **two-valence-particle nucleus** and used for more complex systems → **three- or higher-body forces arising for these systems** *(even if the origin potential contains only two-body terms)* **are not taken into account**

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◆ $$V_{eff} = V_{eff}^{(1)} + V_{eff}^{(2)}$$

$V_{eff}^{(2)}$: **two-body component of the shell-model Hamiltoniam**

$$H_0 + V_{eff}^{(1)}$$ → **single-particle energies**

OUTLINE OF CALCULATION

^{132}Sn core

Valence proton orbits: 0g7/2, 1d5/2, 1d3/2, 0h11/2, 2s1/2

Valence neutron orbits: 1f7/2, 2p3/2, 0h9/2, 2p1/2, 1f5/2, 0i13/2

V_{NN} CD Bonn potential

$V_{low\text{-}k}$ with Λ=2.2 fm^{-1} + Coulomb force for protons

Q-box at second order

U harmonic oscillator with ħω= 7.88 MeV

intermediate hole states – all

intermediate particles states - 5 shell above the Fermi Surface

Proton and neutron single-particle energies (in MeV)

^{133}Sb		^{133}Sn	
$\pi(n,l,j)$	ϵ	$\nu(n,l,j)$	ϵ
$0g_{7/2}$	0.00	$1f_{7/2}$	0.00
$1d_{5/2}$	0.962	$2p_{3/2}$	0.854
$2d_{3/2}$	2.440	$2p_{1/2}$	1.363
$0h_{11/2}$	2.792	$0h_{9/2}$	1.561
$2s_{1/2}$	2.800	$1f_{5/2}$	2.005
		$0i_{13/2}$	2.690

$\pi 2s_{1/2}$ from the expt energy of the $1/2^+$ at 2.15 MeV in ^{137}Cs

$\nu 0i_{13/2}$ from the expt energy of the 10^+ state at 2.43 MeV in ^{134}Sb

Motivation for our study

^{135}Te	^{137}Xe
^{135}Sb	^{137}Sb

- **one-particle spectroscopic factors**

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1. Spectroscopic factors are becoming available from transfer reactions in this region

One-particle transfer reactions are an ideal tool to investigate single-particle excitations

Until 1970-s considerable effort to map out the single-paticle structure of *stable* nuclei

Now possibility of extending transfer reaction studies to *exotic* nuclei through experiments in inverse kinematics

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2. Evolution of the single-neutron and single-proton states

- Survival of the SP character when adding nucleon pairs
- Dependence on the nature of the added particles

➔ **test of pp, nn, pn interaction**

nature Vol 465/27 May/**doi:10.1038/nature09048**

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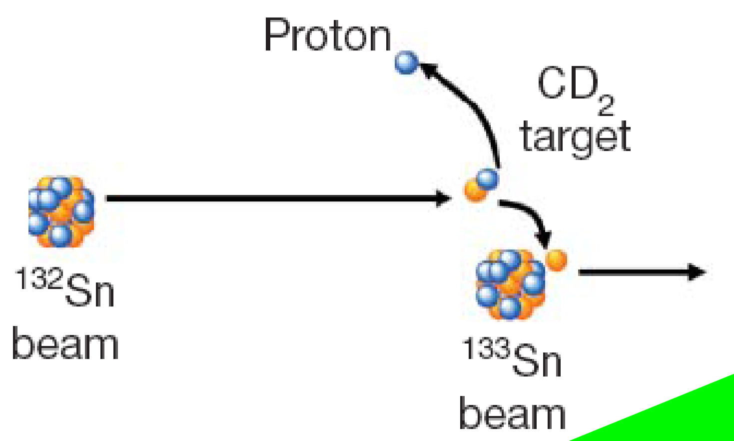

@ HRIBF –Oak Ridge
Protons detected by ORRUBA

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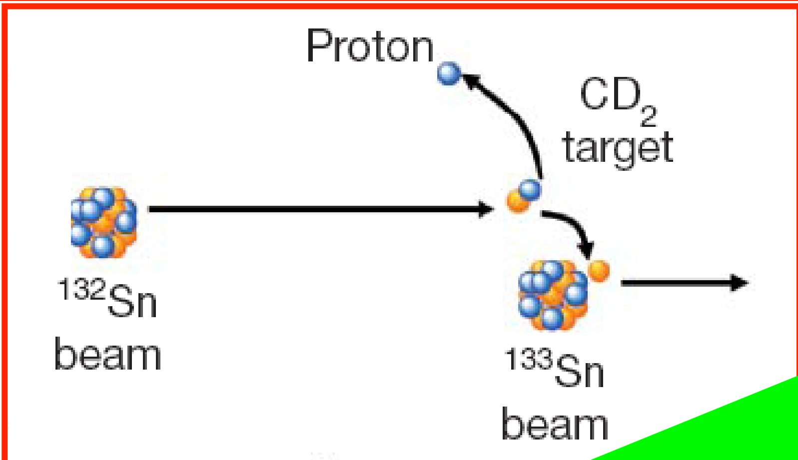

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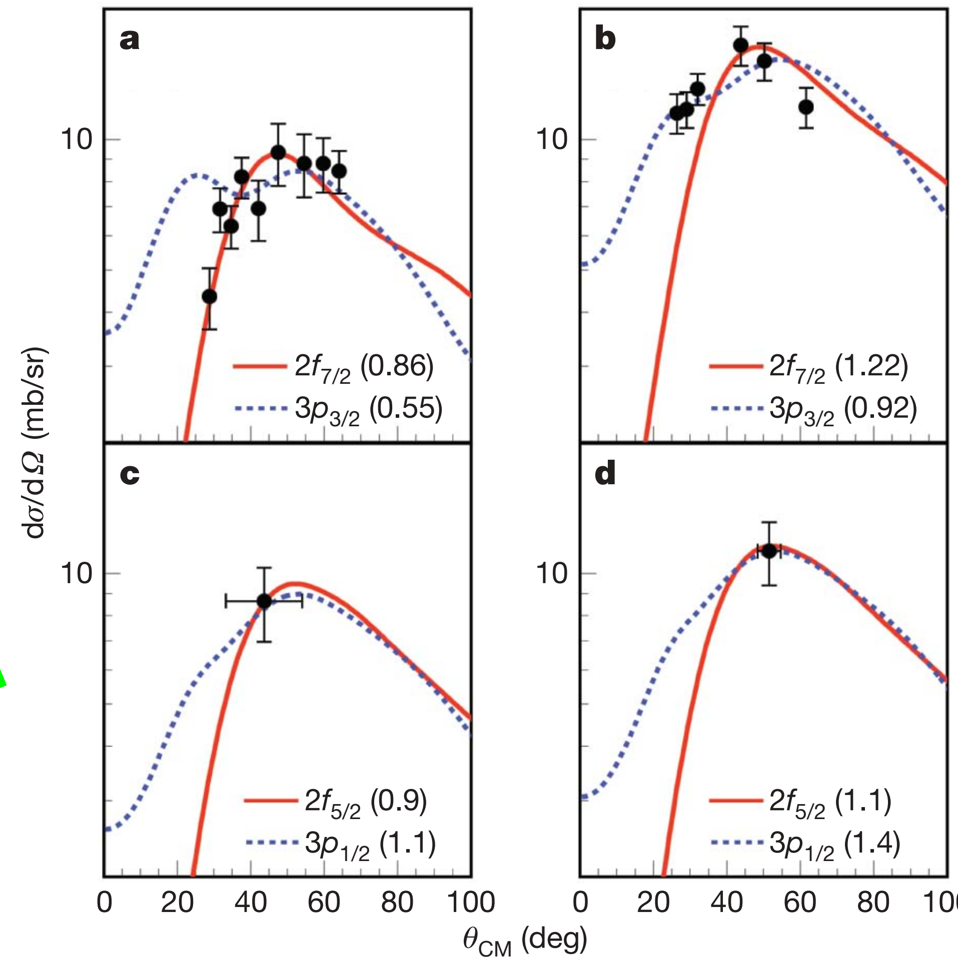

Figure 3 | Angular distributions, expressed as differential cross sections ($d\sigma/d\Omega$), of protons in the centre of mass resulting from the

PHYSICAL REVIEW C **84**, 024325 (2011)

Single-neutron energies outside ^{136}Xe

B. P. Kay,[1,*] J. P. Schiffer,[1] S. J. Freeman,[2] C. R. Hoffman,[1] B. B. Back,[1] S. I. Baker,[1] S. Bedoor,[3] T. Bloxham,[4] J. A. Clark,[1] C. M. Deibel,[1,5] A. M. Howard,[2] J. C. Lighthall,[1,3] S. T. Marley,[1,3] K. E. Rehm,[1] D. K. Sharp,[2] D. V. Shetty,[3] J. S. Thomas,[2] and A. H. Wuosmaa[3]

[1]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[2]*School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom*
[3]*Physics Department, Western Michigan University, Kalamazoo, Michigan 49008, USA*
[4]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[5]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*

(Received 4 July 2011; published 29 August 2011)

The single-neutron properties of the $N = 83$ nucleus ^{137}Xe have been studied using the ^{136}Xe(d,p) reaction in inverse kinematics at a beam energy of 10 MeV/u. The helical-orbit spectrometer, HELIOS, at Argonne National Laboratory was used to analyze the outgoing protons, achieving an excitation-energy resolution of ∼100 keV. Extraction of absolute cross sections, angular distributions, and spectroscopic factors has led to a more complete understanding of the single-neutron strength in ^{137}Xe. In particular, the centroids of the $\nu h_{9/2}$ and $\nu i_{13/2}$ strengths appear to evolve through the $N = 83$ isotones in a manner consistent with the action of the tensor force.

@ATLAS – Argonne Nat Lab
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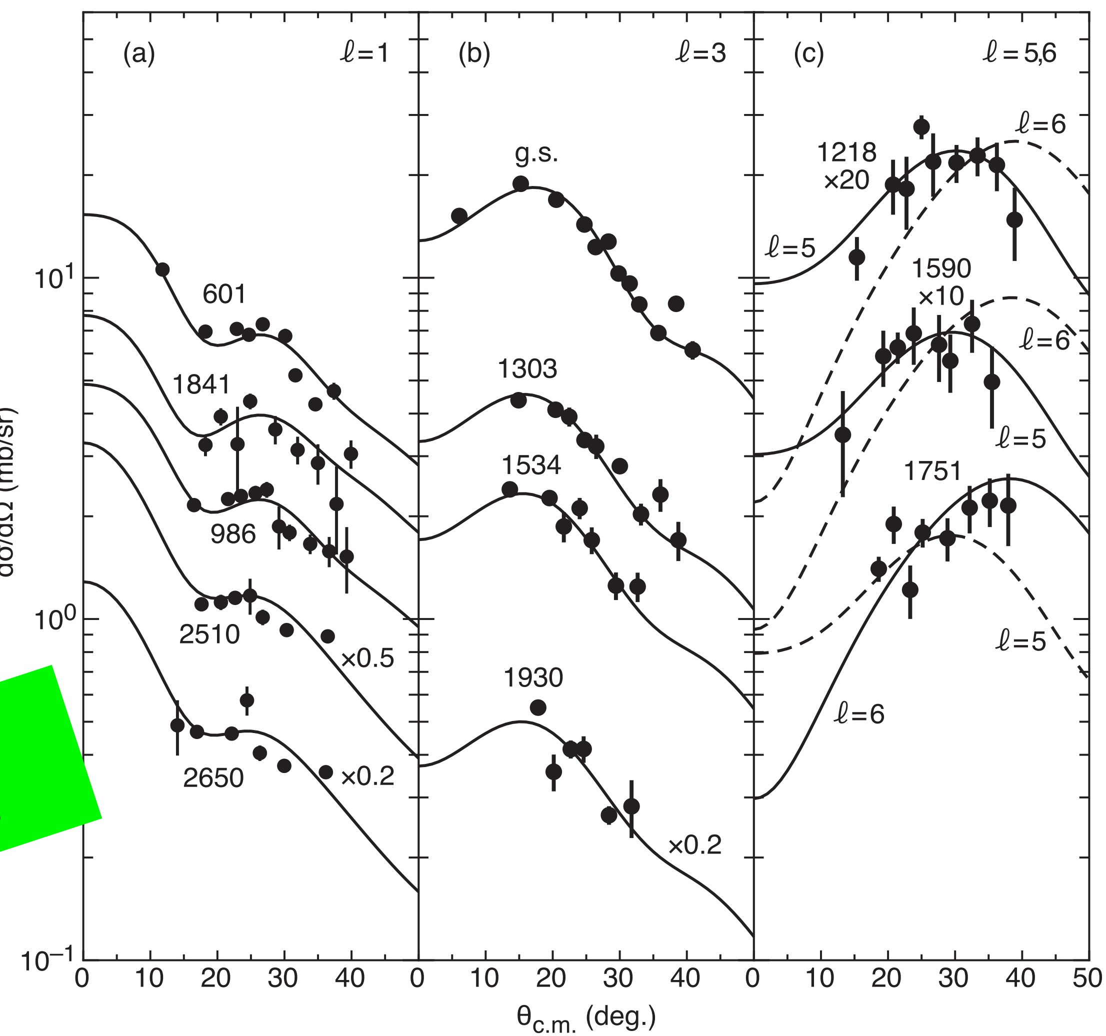

FIG. 3. Angular distributions for the outgoing protons in the $d(^{136}\mathrm{Xe},p)^{137}\mathrm{Xe}$ reaction.

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PHYSICAL REVIEW VOLUME 175, NUMBER 4 20 NOVEMBER 1968

^{136}Xe(d,p) and ^{136}Xe(d,t) Reactions*

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Z. Phys. A – Hadrons and Nuclei 340, 339–340 (1991)

Zeitschrift für Physik A Hadrons and Nuclei

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Short note

Investigation of the (d, p)-reaction on ^{136,132}Xe in inverse kinematics*

G. Kraus[1], P. Egelhof[1], H. Emling[1], E. Grosse[1], W. Henning[1], R. Holzmann[1], H.J. Körner[2], J.V. Kratz[3], R. Kulessa[4], Ch. Schießl[2], J.P. Schiffer[5], W. Wagner[2], W. Walus[4], and H.J. Wollersheim[1]

The one-neutron transfer reactions d(^{132,136}Xe, p)^{133,137}Xe have been investigated in inverse kinematics with xenon beams incident on deuterium loaded titanium targets. The angular distributions of the protons, measured with a detector array of 100 PIN-photodiodes, have been analyzed using standard DWBA. Generally, good agreement is obtained with results previously obtained in reactions induced by light-ion beams.

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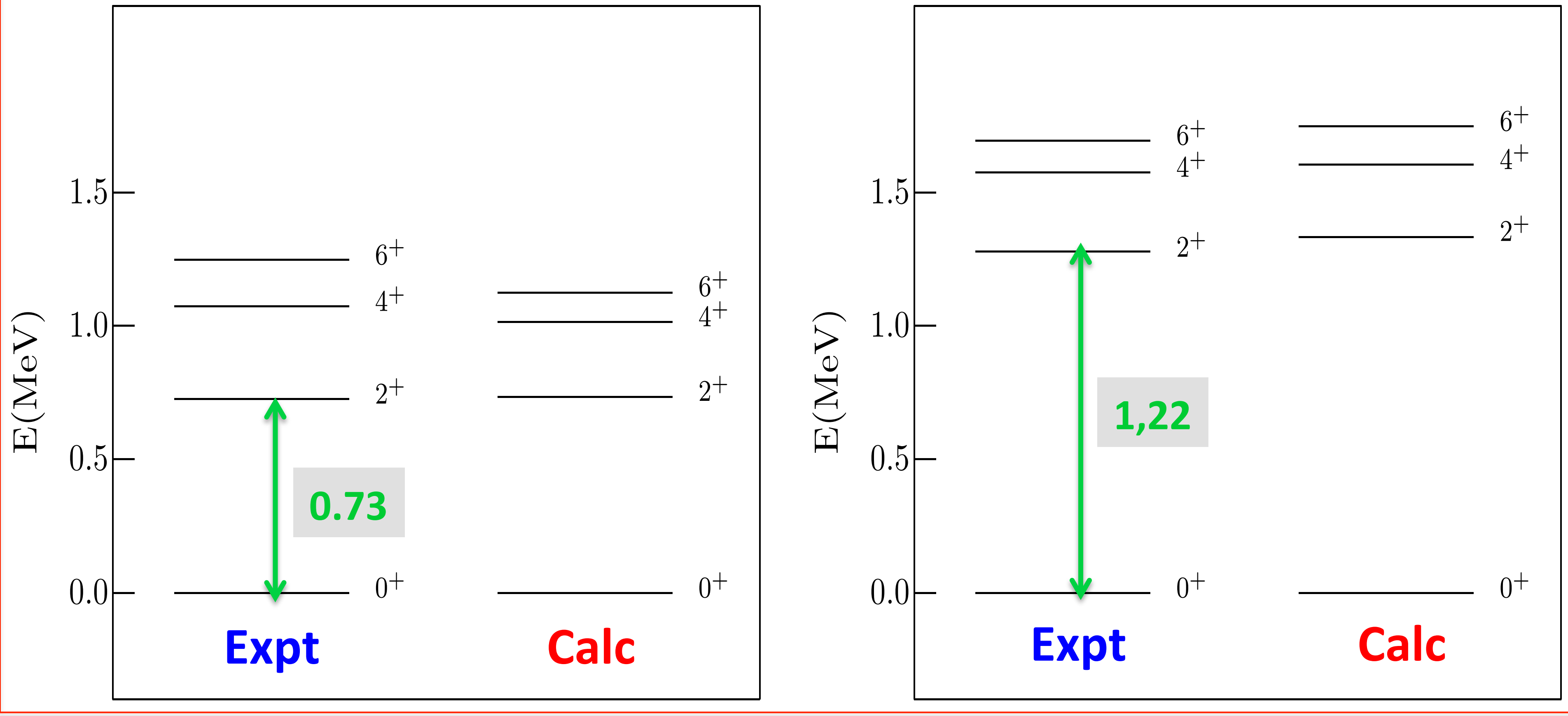
The experimental results and the overall good agreement with existing light-ion induced data indicate, that the method of inverse kinematics - using heavy ion beams incident on light target nuclei - can be a useful tool for spectroscopic investigations in nuclear transfer reactions on nuclei far from stability. The quality of the data can be

Test of the two-body matrix elements

- **nn** ^{134}**Sn** with *two neutrons* in the 82-126 shell
- **pp** ^{134}**Te** with *two protons* in the 50-82 shell
- **pn** ^{134}**Sb** with *a proton* in the 50-82 shell and *a neutron* in the 82-126 shell

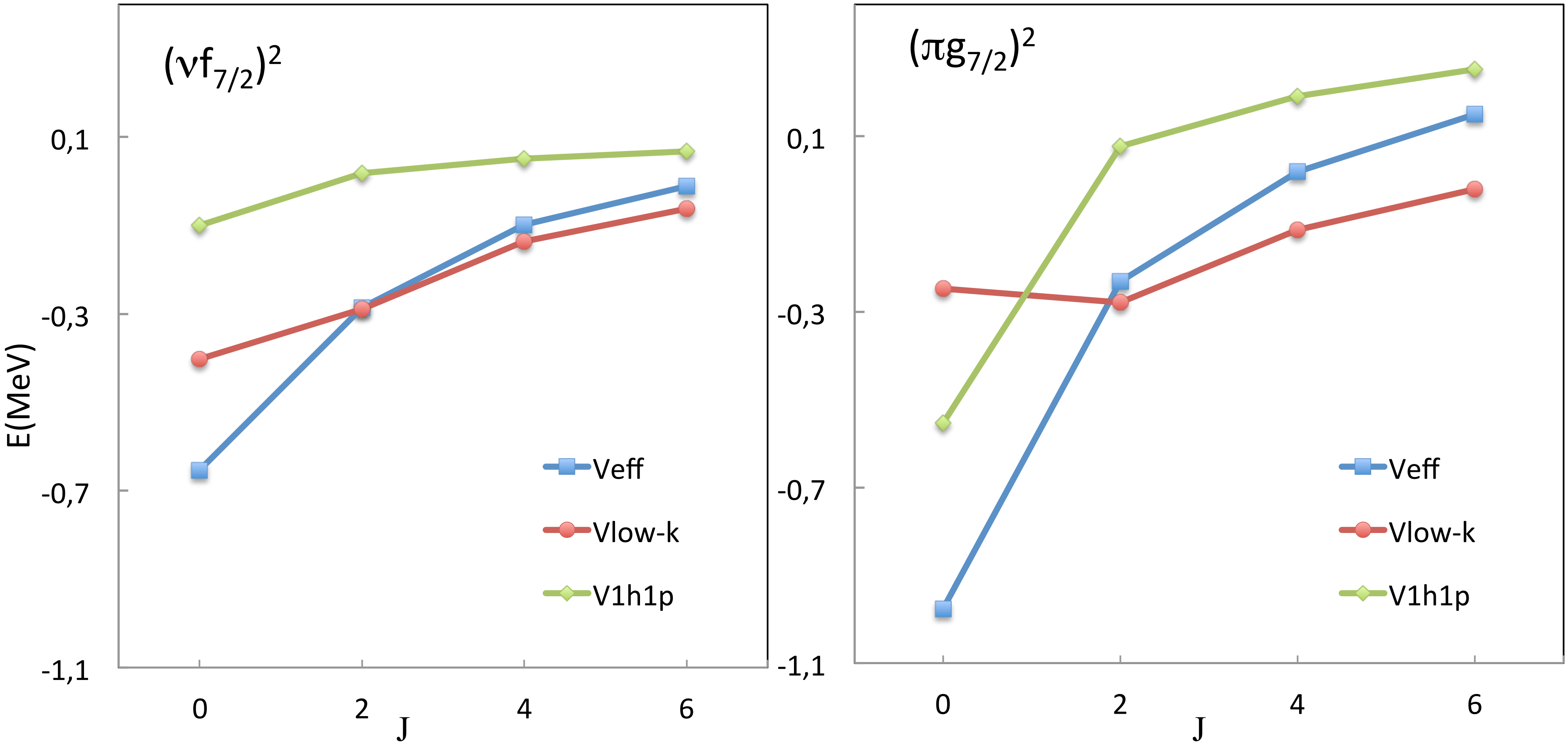
$^{134}_{50}Sn_{84}$ $^{134}_{52}Te_{82}$



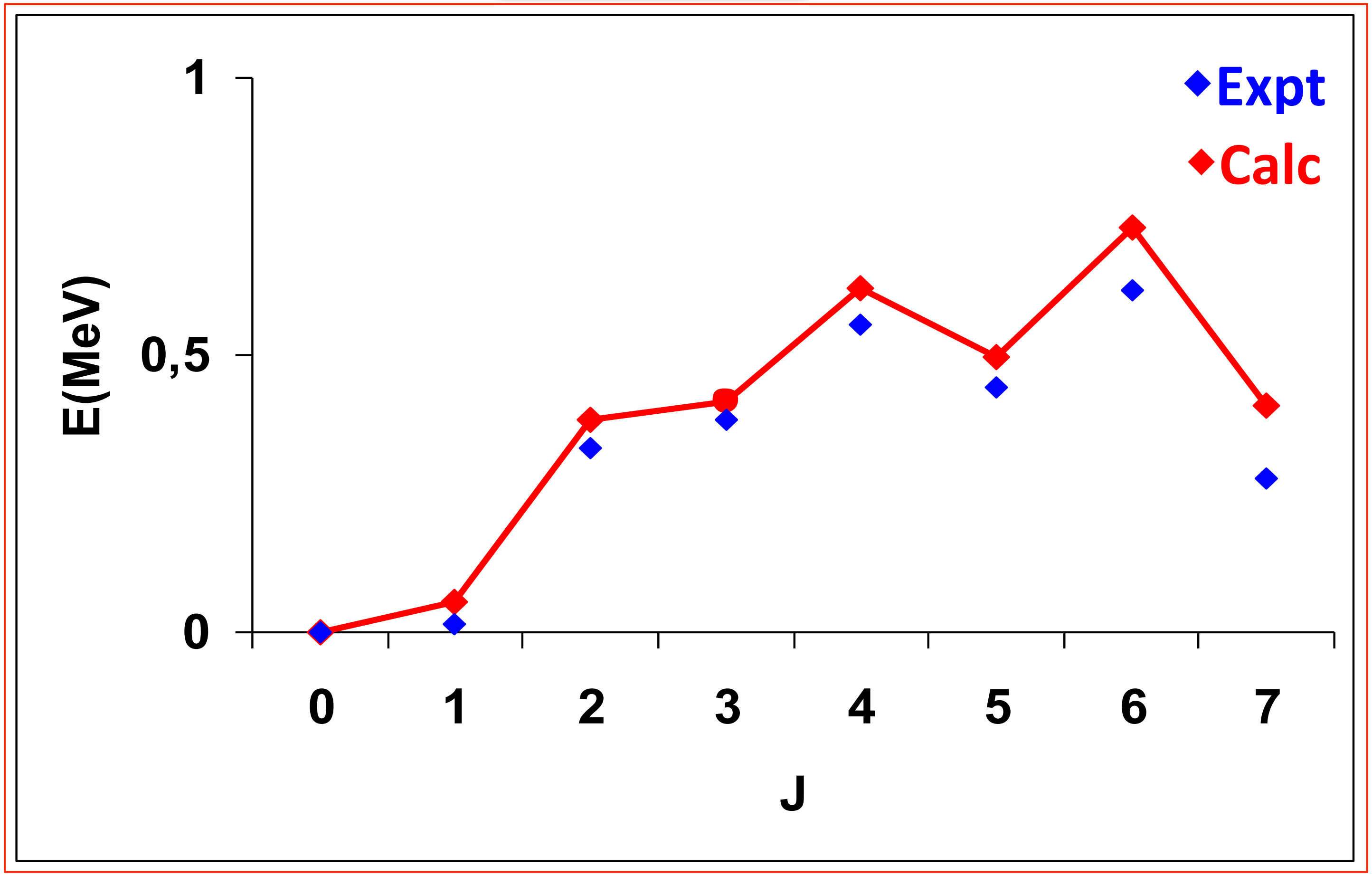
$(\nu f_{7/2})^2$ configuration

$(\pi g_{7/2})^2$ configuration

Diagonal matrix elements of interaction for the $(\nu f_{7/2})^2$ and $(\pi g_{7/2})^2$ configurations



$^{134}_{51}Sb_{83}$



$\pi g_{7/2}\nu f_{7/2}$ configuration

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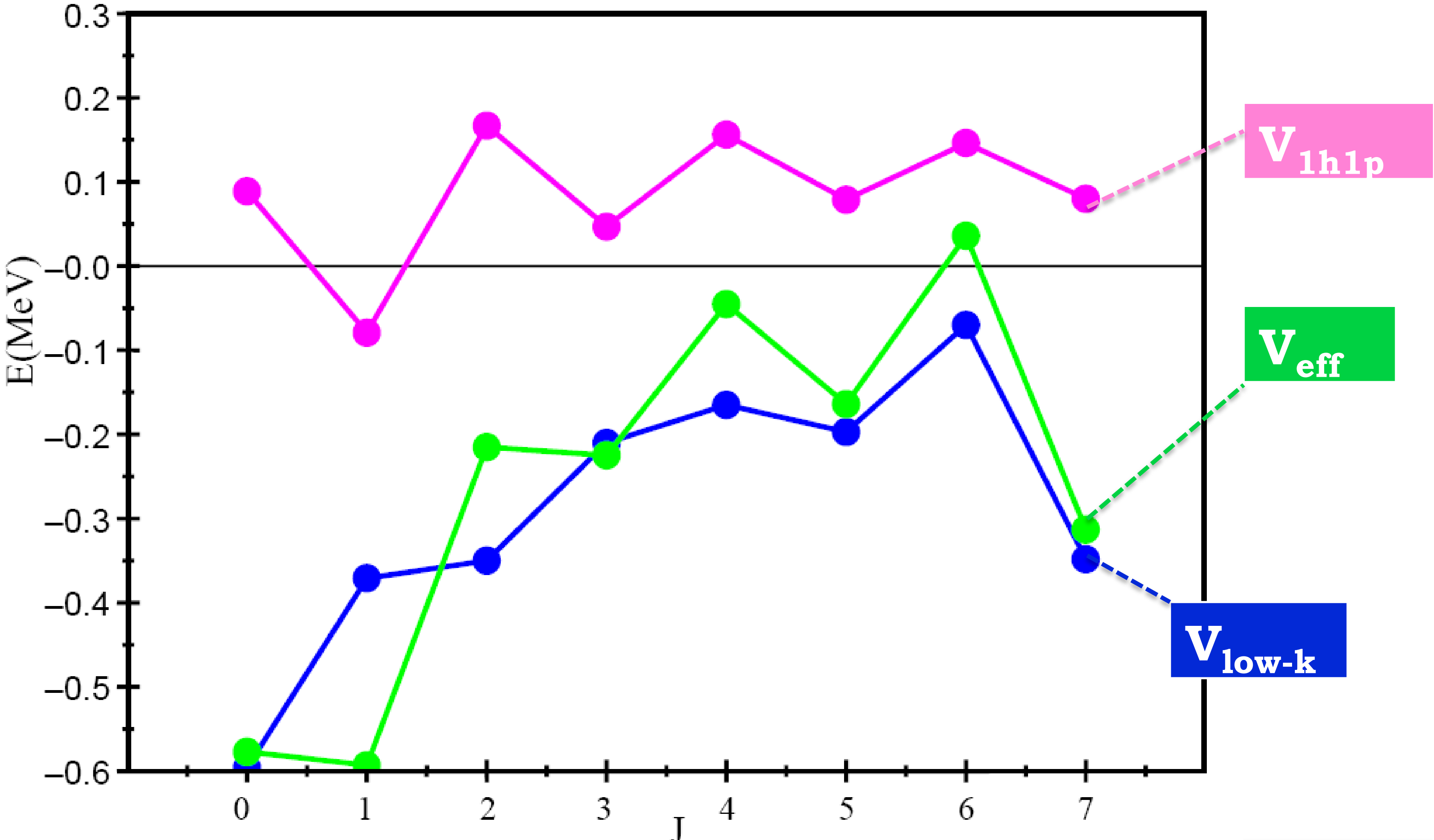

^{137}Xe

Expt			Calc		
J^π	E(MeV)	C^2S [1]	J^π	E(MeV)	C^2S
$7/2^-$	0.0	0.94	$7/2^-$	0.0	0.86
$3/2^-$	0.601	0.52	$3/2^-$	0.728	0.57
$1/2^-,3/2^-$	0.986	0.35	$1/2^-$	1.127	0.43
$9/2^-$	1.218	0.43	$9/2^-$	1.327	0.72
$5/2^-$	1.303	0.22	$5/2^-$	1.349	0.17
$5/2^-,7/2^-$	1.534	0.12	$7/2^-$	1.589	0.05
			$5/2^-$	1.666	0.04
$9/2^-$	1.590	0.24	$9/2^-$	1.584	0.01
			$(5/2^-)_5$	2.039^c	0.20
$13/2^+$	1.751	0.84	$13/2^+$	2.082	0.75

[1] B. P. Kay et al, PRC 84, 024325 (2011)

uncertainties in expt SF ≈ 25%

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^{135}Te

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$7/2^-$	0.0*	3	$7/2^-$	0.0	0.86
$3/2^-$	0.659*	1	$3/2^-$	0.726	0.63
$1/2^-$	1.083*	1	$1/2^-$	1.110	0.45
$5/2^-$	1.127		$5/2^-$	1.119	0.12
$9/2^-$	1.246		$9/2^-$	1.302	0.18
			$7/2^-$	1.336	
$7/2^-,9/2^-$	1.380		$9/2^-$	1.346	0.51
			$3/2^-$	1.721	0.27
$3/2^-,5/2^-$	1.837*	-	$1/2^-$	1.947	0.32
			$(5/2^-)_6$	2.238	0.41
$13/2^+$	2.109		$13/2^+$	2.268	0.72

* preliminary $^{134}Te(d,p)$ experiment by J.A. Cizewski et al, AIP Conf. Proc. 1090, 463(2009)

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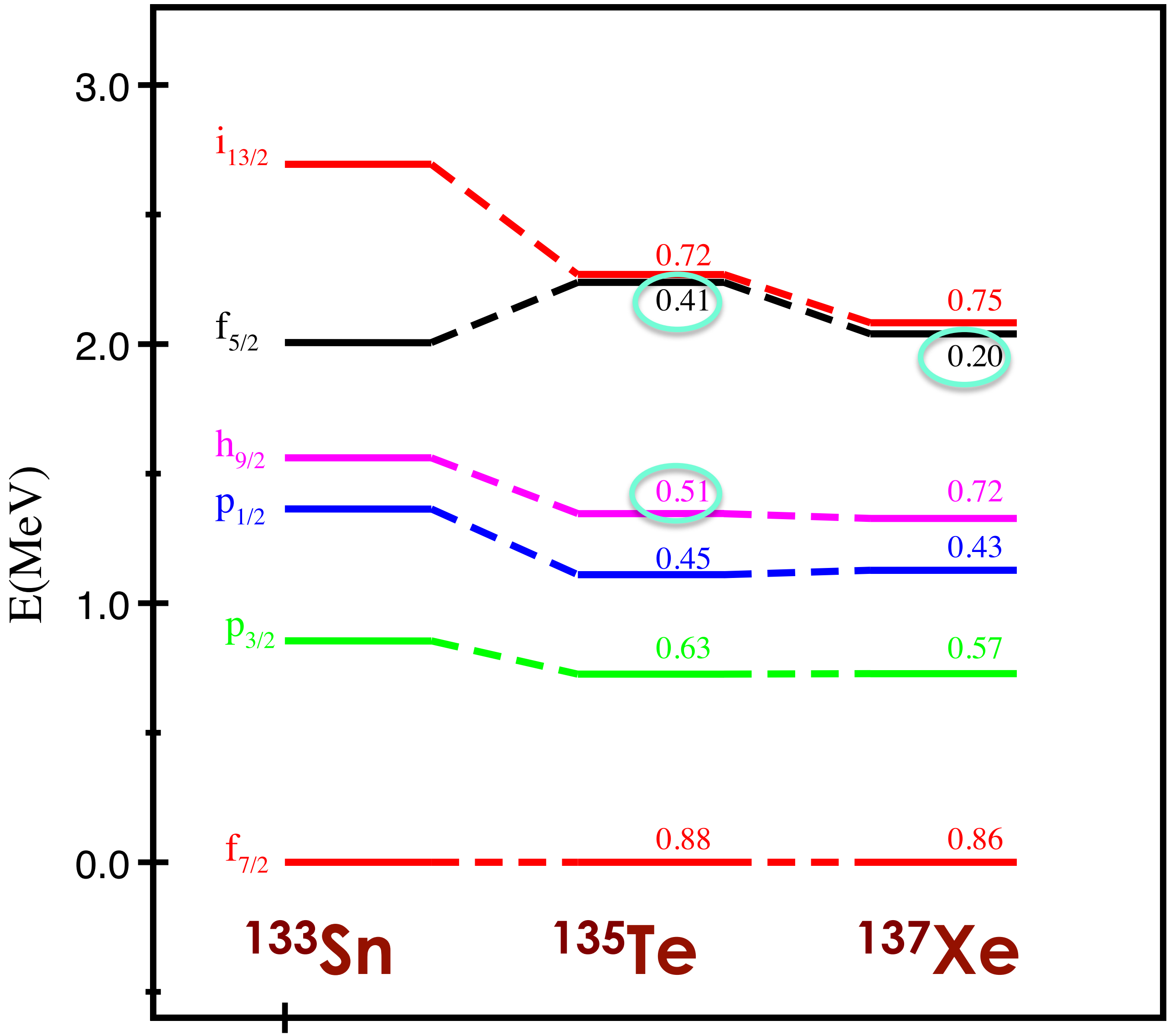
$3/2^-$		$5/2^-$	
E(MeV)	**C^2S**	**E(MeV)**	**C^2S**
1.81	**0.00**	**1.71**	**0.00**
		1.82	**0.06**
		2.01	**0.06**

* preliminary ^{134}Te(d,p) experiment by J.A. Cizewski et al, AIP Conf. Proc. 1090, 463(2009)

States with the largest single-neutron strength



^{135}Sb

Expt		Calc		
J^π	E(MeV)	J^π	E(MeV)	C^2S
$7/2^+$	0.0	$7/2^+$	0.0	0.74
$5/2^+$	0.282	$5/2^+$	0.387	0.42
$3/2^+$	0.440	$3/2^+$	0.497	0.07
$1/2^+$	0.523	$1/2^+$	0.659	0.07
		$(5/2^+)_2$	0.928	0.23
		$(3/2^+)_{12}$	2.600	0.32
		$(1/2^+)_{12}$	3.199	0.32
		$11/2^-$	2.652	0.52
		$(11/2^-)_5$	3.522	0.21

^{137}Sb

Calc		
J^π	E(MeV)	C^2S
$7/2^+$	0.0	0.71
$5/2^+$	0.186	0.56
$3/2^+$	0.333	0.12
$1/2^+$	0.403	0.11
$11/2^-$	2.587	0.38

yrast states & states with C^2S >0.2

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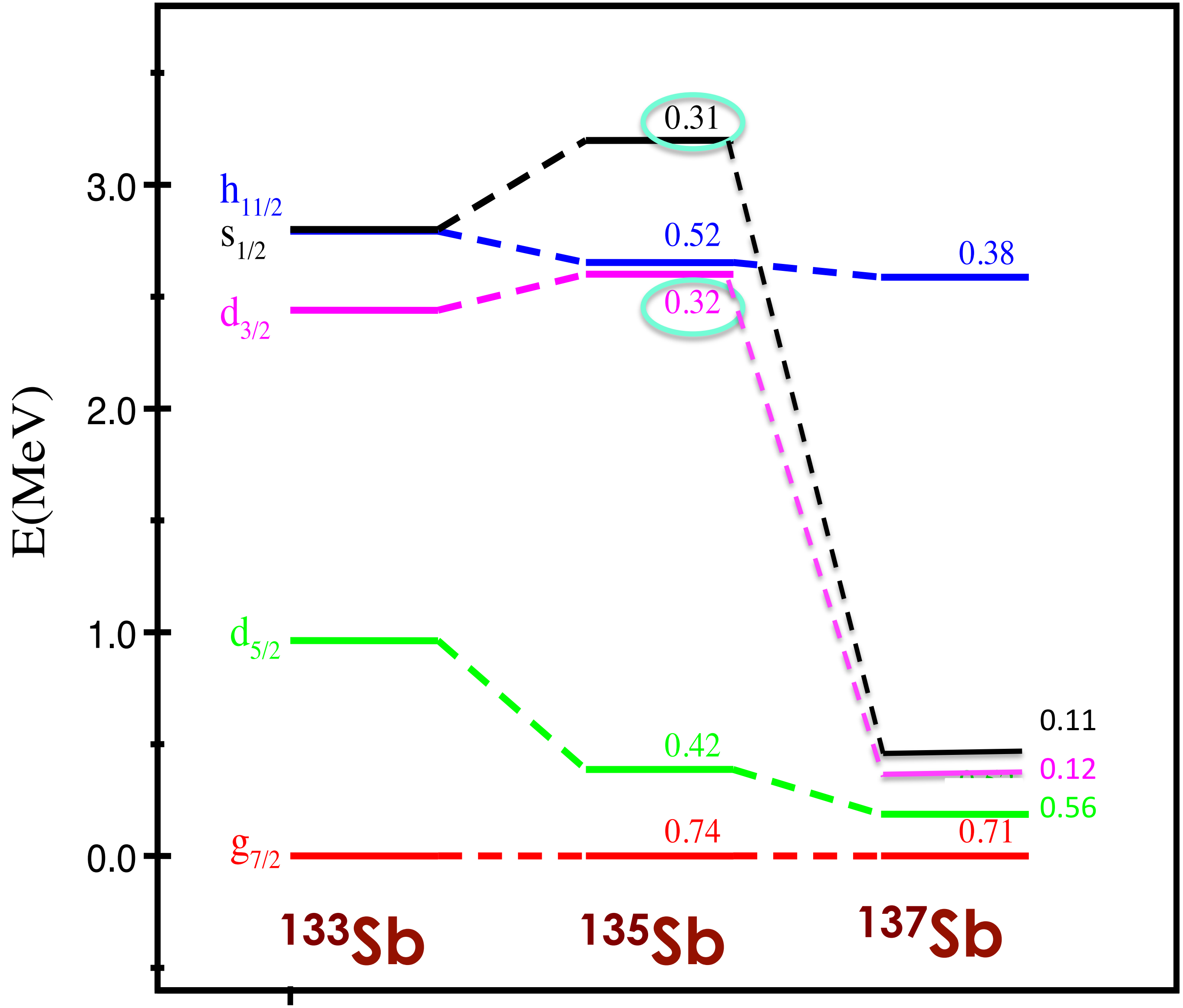
	Jπ	i	$\Sigma_i C^2S$
^{135}Sb	$1/2^+$	12	0.67
	$3/2^+$	12	0.63
^{137}Sb	$1/2^+$	30	0.38
	$3/2^+$	30	0.52

yrast states & states with C^2S >0.2

States with the largest single-proton strength



More fragmentation of the single-particle strength in Sb isotopes than in N=83 isotones

due to the pairing force weaker for neutrons in the 82-126 shell than for protons in the Z=50-82 shell

More fragmentation of the single-particle strength in Sb isotopes than in N=83 isotones

due to the pairing force weaker for neutrons in the 82-126 shell than for protons in the Z=50-82 shell

^{134}Te

2 proton particles in the 50-82 shell

$\Delta_p = E_{exc}(2^+_1) = 1.28$ MeV

strong renormalization effects in the effective interaction induced by the core polarization

^{134}Sn

2 neutron particles in the 82-126 shell

$\Delta_n = E_{exc}(2^+_1) = 0.73$ MeV

weak renormalization effects in the effective interaction induced by the core polarization

Single-particle energies as the centroid of the single-particle strengths

$$\varepsilon_j^c = \sum_f C^2 S_{fj} E_{fj}$$

E_{fj} energies of the final states of the one-nucleon stripping reaction

J.B. French, E. Fermi School (1965)
M. Baranger,NP A**149**,225(1970)

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J.B. French, E. Fermi School (1965)
M. Baranger, NP A**149**,225(1970)

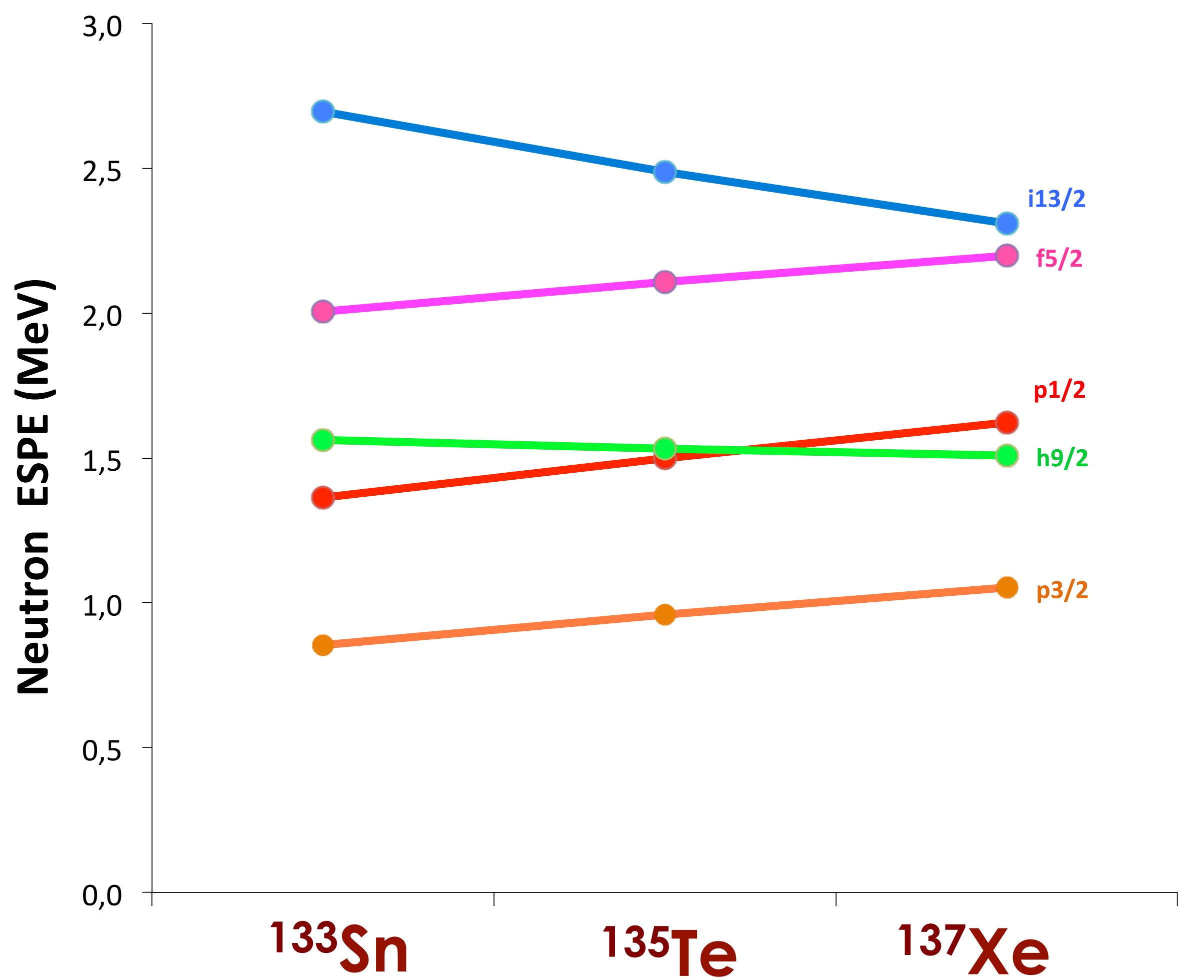
$$\overline{\varepsilon}_j = \varepsilon_j + \sum_{j'} V^M(jj')N_{j'}$$

V^M monopole interaction

N_j number of nucleons in the orbit j

A. Umeya and K. Muto,PRC **74**,034330 (2006)

$$\bar{\varepsilon}_{j_\nu} = \varepsilon_{j_\nu} + \sum_{j_\pi} V^M(j_\nu j_\pi) N_{j_\pi}$$



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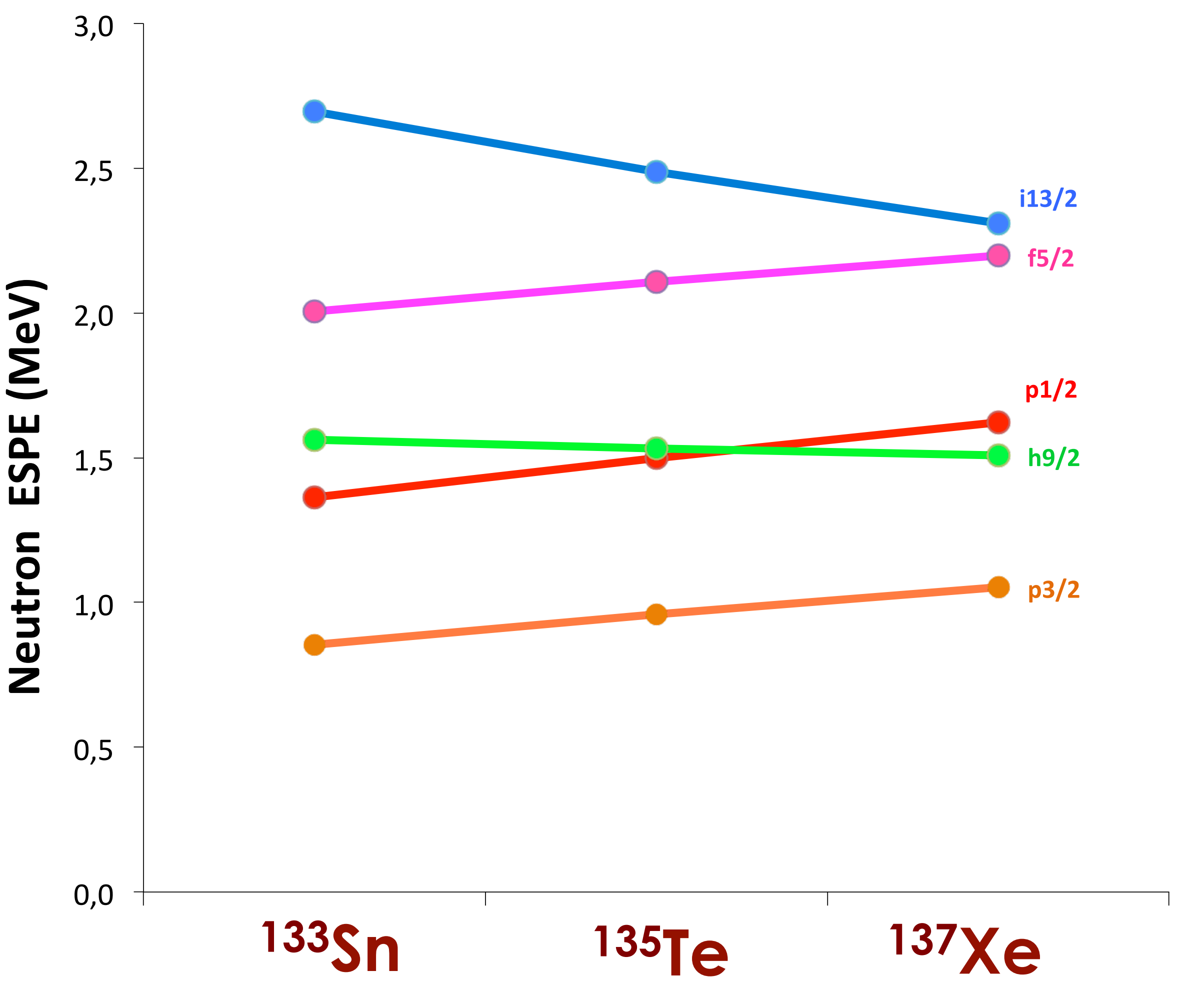


jπ	N(jπ) ^{134}Te	N(jπ) ^{136}Xe
g7/2	1.6	3.1

jν	V(πg7/2,jν)
f7/2	-0.18
f5/2	-0.11
p3/2	-0.11
p1/2	-0.09
h9/2	-0.20
i13/2	-0.33

$$\bar{\varepsilon}_{j_\nu} = \varepsilon_{j_\nu} + \sum_{j_\pi} V^M(j_\nu j_\pi) N_{j_\pi}$$

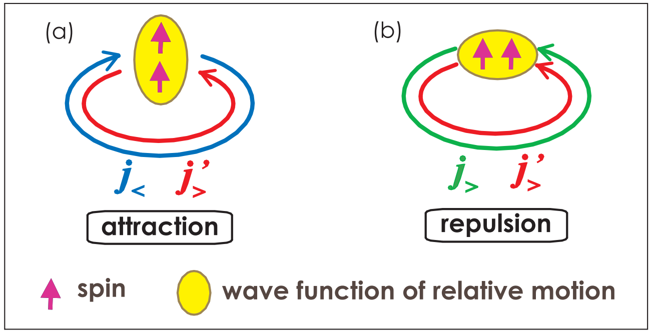
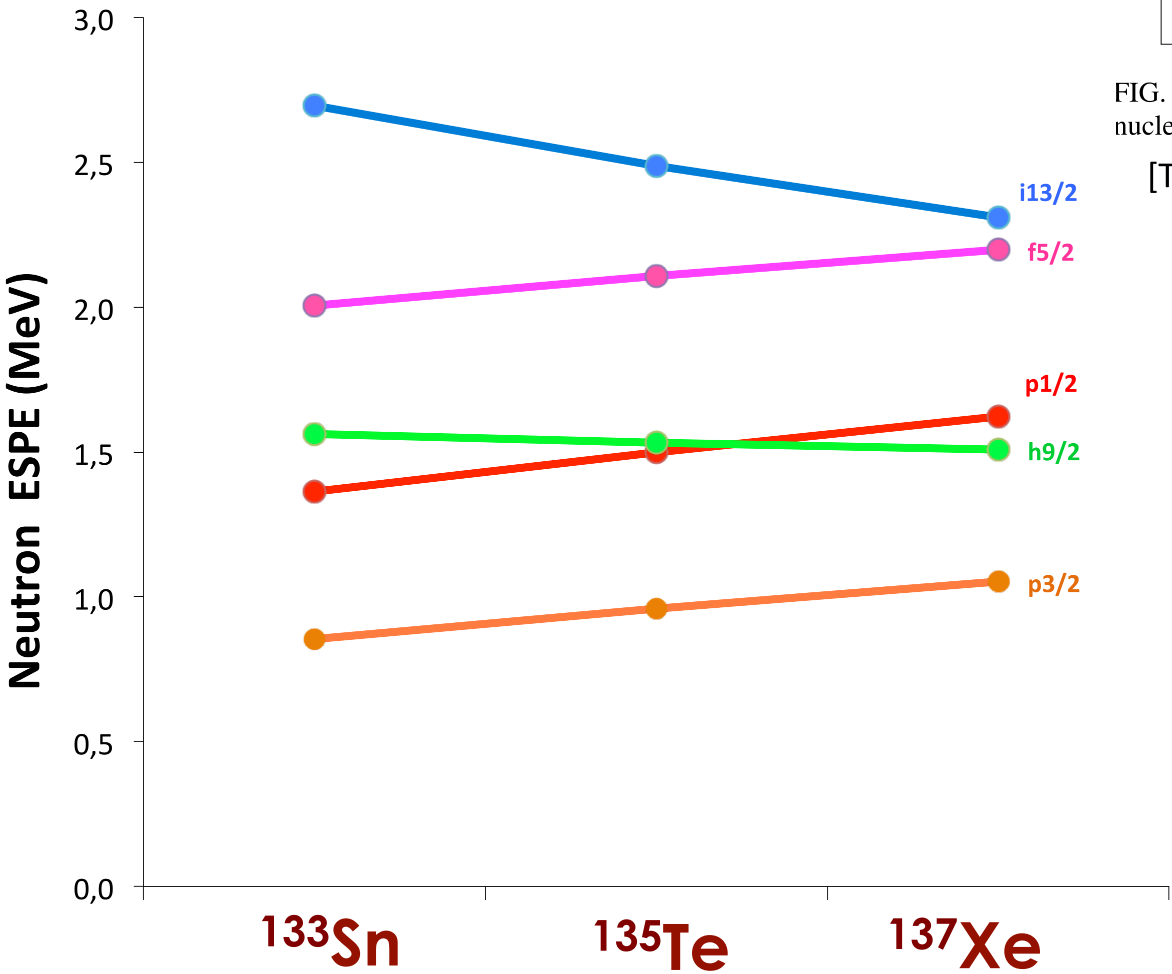


FIG. 2 (color). Intuitive picture of the tensor force acting two nucleons on orbits j and j'.

[T. Otska et al, PRL 95, 232502 (2005)]



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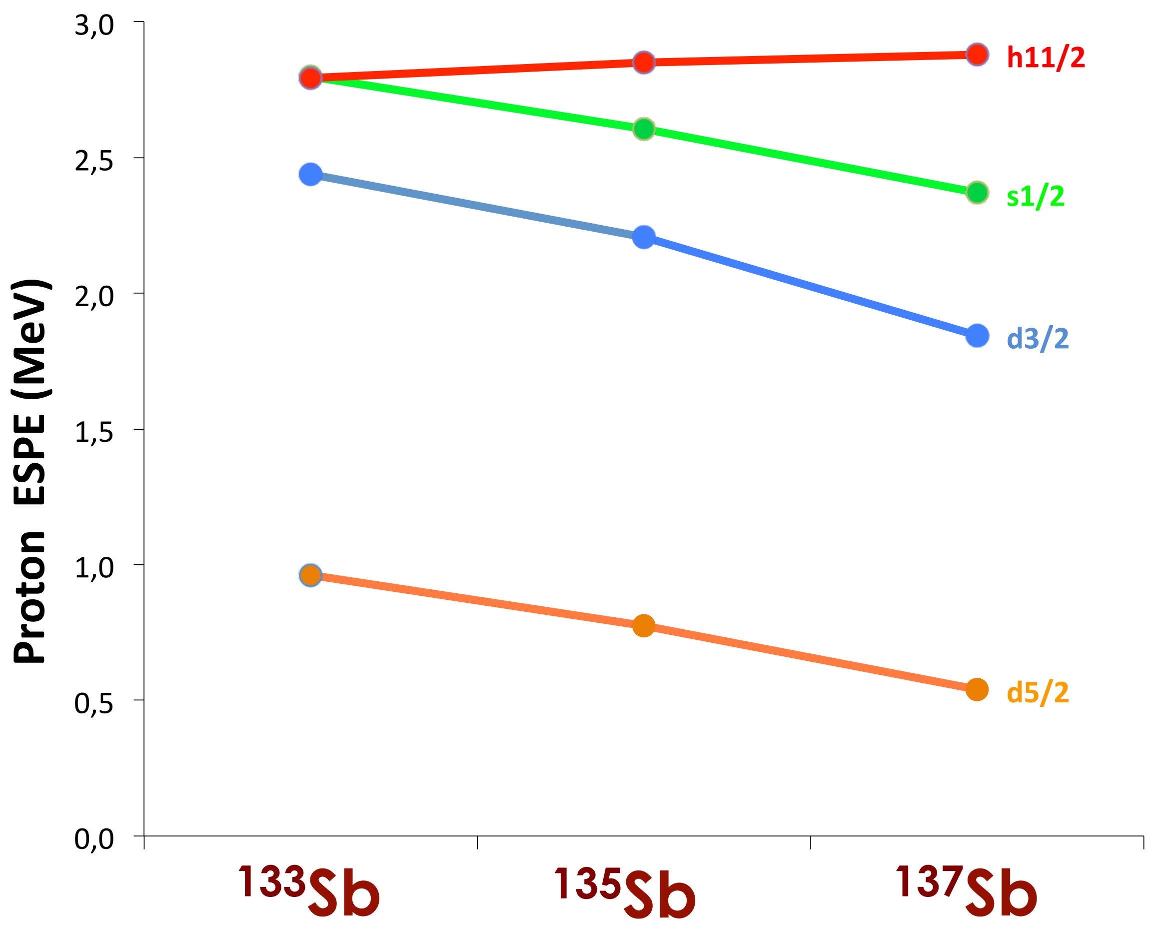
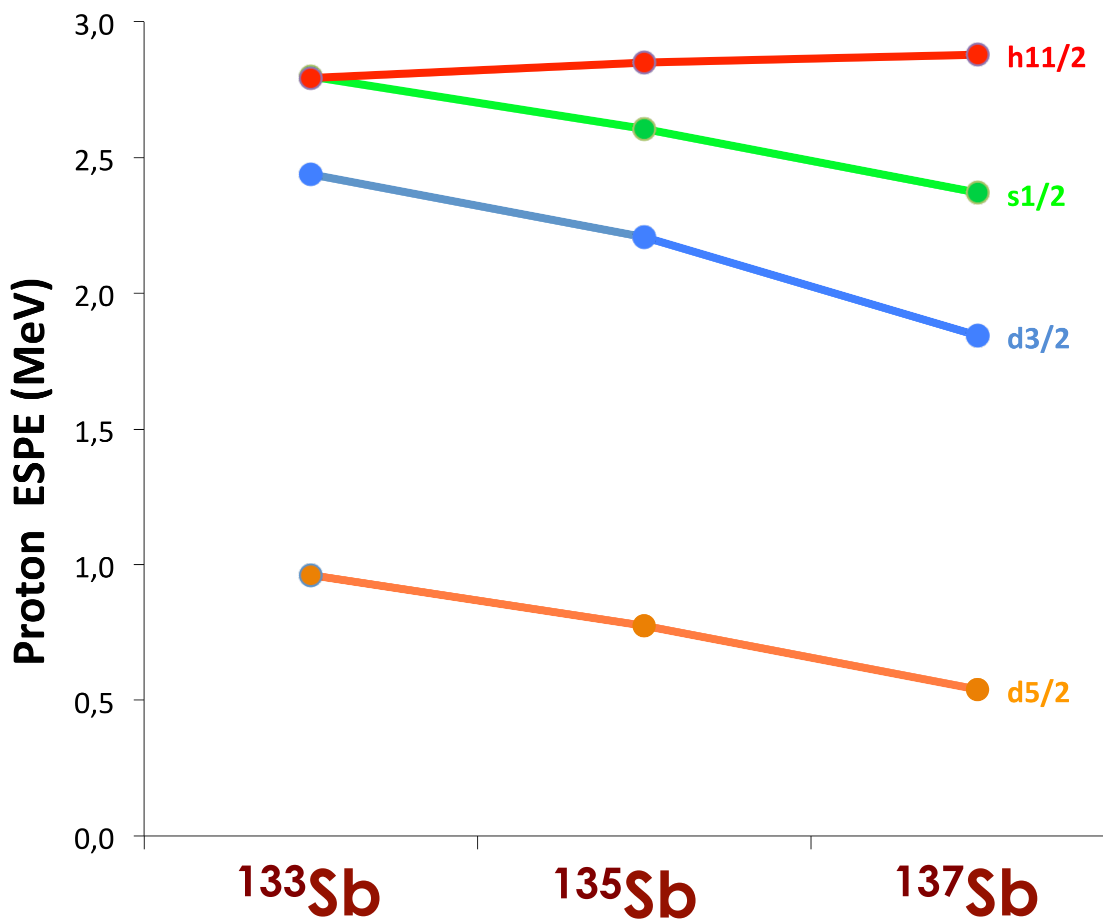
$$\bar{\varepsilon}_{j_\pi} = \varepsilon_{j_\pi} + \sum_{j_\nu} V^M(j_\pi j_\nu) N_{j_\nu}$$



$$\bar{\varepsilon}_{j_\pi} = \varepsilon_{J_\pi} + \sum_{j_\nu} V^M(j_\pi j_\nu) N_{j_\nu}$$



jν	N(jν) ^{134}Sb	N(jν) ^{136}Sb
f7/2	1.6	3.2

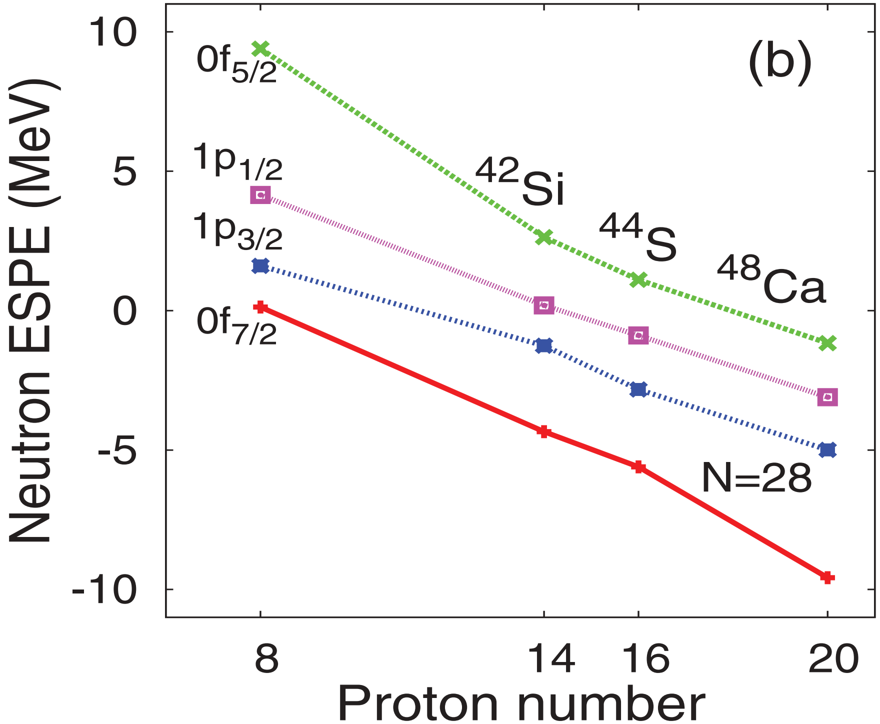
jπ	V(νf7/2, jπ)
g7/2	-0.18
d5/2	-0.28
d3/2	-0.35
s1/2	-0.27
h11/2	-0.13

PHYSICAL REVIEW C **86**, 034314 (2012)

Nuclear shell evolution and in-medium NN interaction

N. A. Smirnova,[1] K. Heyde,[2] B. Bally,[1] F. Nowacki,[3] and K. Sieja[3]

… global variation of the single-particle energy over a region of isotones (isotopes) is mainly due to the central part of the nucleon-nucleon interaction. On the other hand, the local variations (differences of single particle energies) in shell-gaps and in spin-orbit energy splitting are determined by the interplay of the central, vector, and tensor parts…



…the behavior of a given ESPE is governed mainly by the triplet- even component of the central part

Conclusions

- **Realistic shell model provides an appropriate tool for nuclear structure studies**

Possibility to understand

◆ the properties of nuclei in terms of the forces among nucleons

◆ deficiencies and limits of the theory, because of the absence of free parameters

- **Comparison with available data in ^{132}Sn region evidences the reliability of our interaction matrix elements**

- **Open problems**

Role of genuine and effective three-body forces

Naples group

L. Coraggio

A. Covello

A. G.

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Thanks for your attention