Study of shell evolution around the doubly magic ^{208}Pb via a multinucleon transfer reaction with an unstable beam

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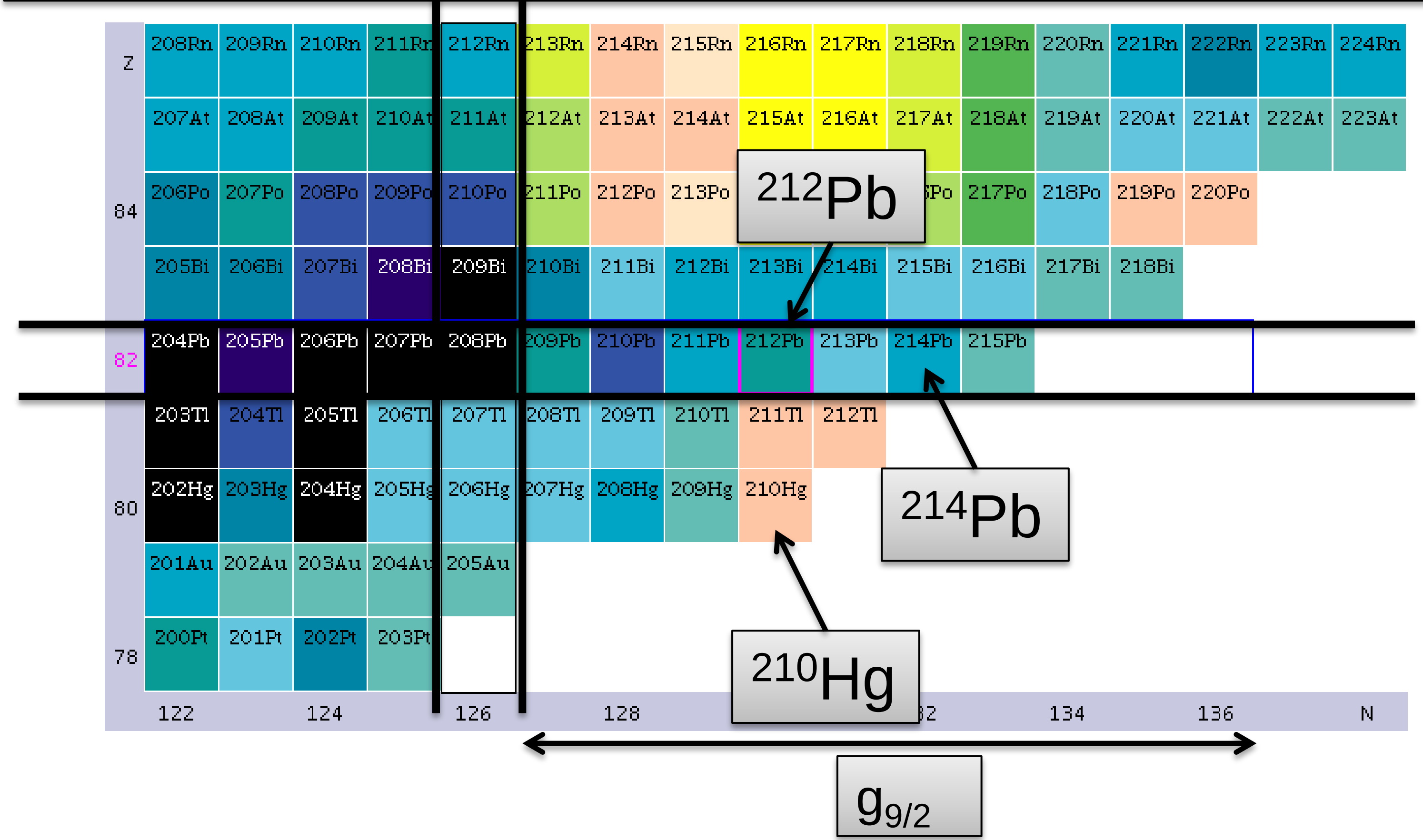
The Z=82 and beyond N=126

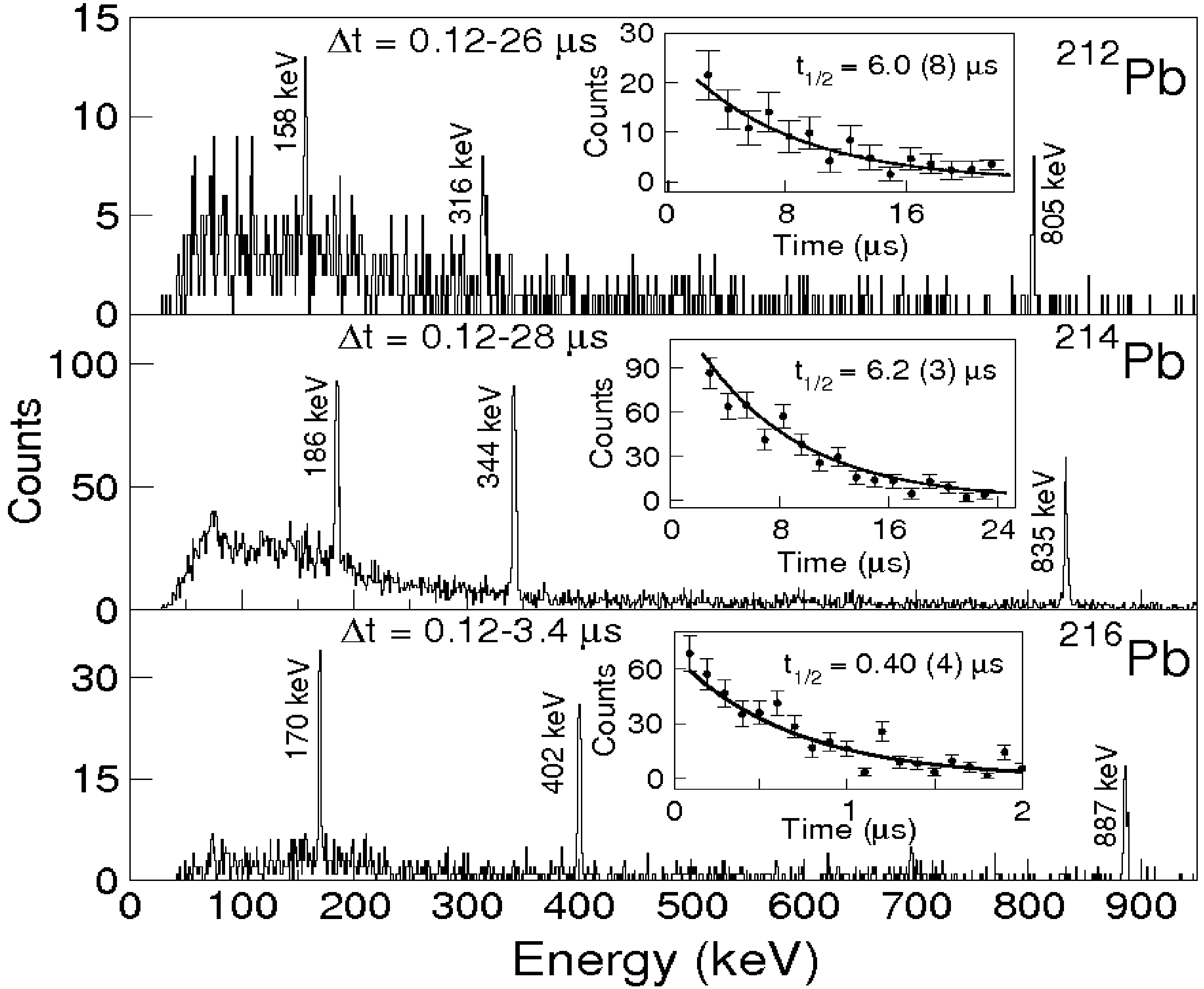
The region around ^{208}Pb has been very difficult to populate experimentally due to its large A and Z. We want to study the developmet of nuclear structure in the nuclei beyond N=126. More especifically: ^{212,214}Pb and ^{210}Hg.

Proof of principle that multinucleon transfer reactions with RIB is efficient to populate neutron-rich heavy binary partners and represents a competitive method to fragmentation

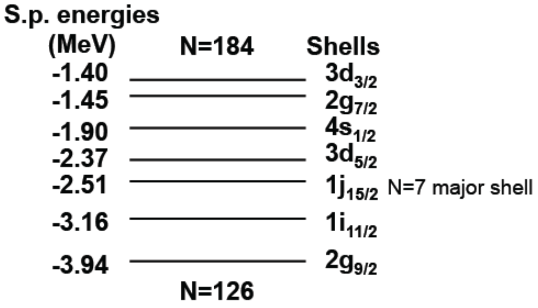


Z	208Rn	209Rn	210Rn	211Rn	212Rn	213Rn	214Rn	215Rn	216Rn	217Rn	218Rn	219Rn	220Rn	221Rn	222Rn	223Rn	224Rn
	207At	208At	209At	210At	211At	212At	213At	214At	215At	216At	217At	218At	219At	220At	221At	222At	223At
84	206Po	207Po	208Po	209Po	210Po	211Po	212Po	213Po			6Po	217Po	218Po	219Po	220Po		
	205Bi	206Bi	207Bi	208Bi	209Bi	210Bi	211Bi	212Bi	213Bi	214Bi	215Bi	216Bi	217Bi	218Bi			
82	204Pb	205Pb	206Pb	207Pb	208Pb	209Pb	210Pb	211Pb	212Pb	213Pb	214Pb	215Pb					
	203Tl	204Tl	205Tl	206Tl	207Tl	208Tl	209Tl	210Tl	211Tl	212Tl							
80	202Hg	203Hg	204Hg	205Hg	206Hg	207Hg	208Hg	209Hg	210Hg								
	201Au	202Au	203Au	204Au	205Au												
78	200Pt	201Pt	202Pt	203Pt													
	122		124		126		128				32		134		136		N

Fragmentation: ^{212,214,216}Pb: 8$^+$ isomer



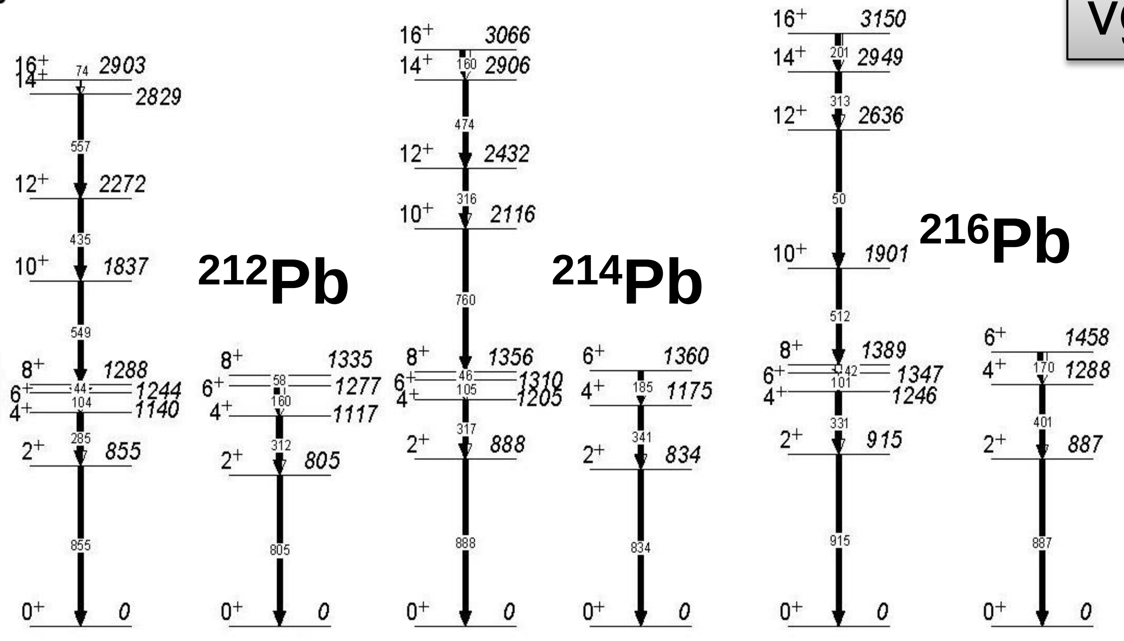
Shell Model calculations Kuo-Herling



Calculations with Antoine and Nathan codes and K-H interaction

E.K. Warburton and B.A. Brown PRC43, 602 (1991).

$vg_{9/2}^{3}\ i_{11/2}^{1}$

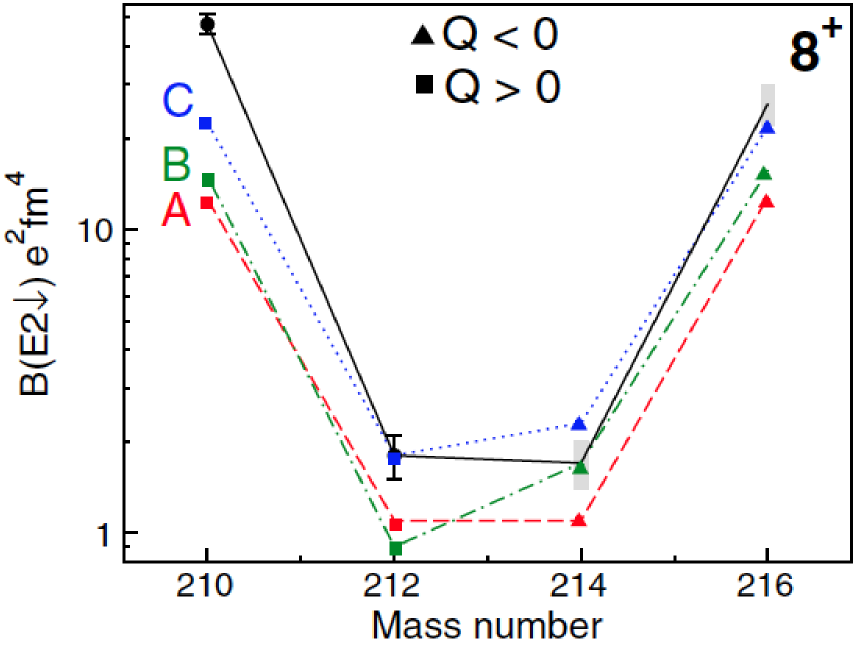


$B(E2: 8^+ \rightarrow 6^+)$

$vg_{9/2}^{2}$

th. exp. **th. exp** **th. exp.**

Effective 3-body interaction



— Exp. data

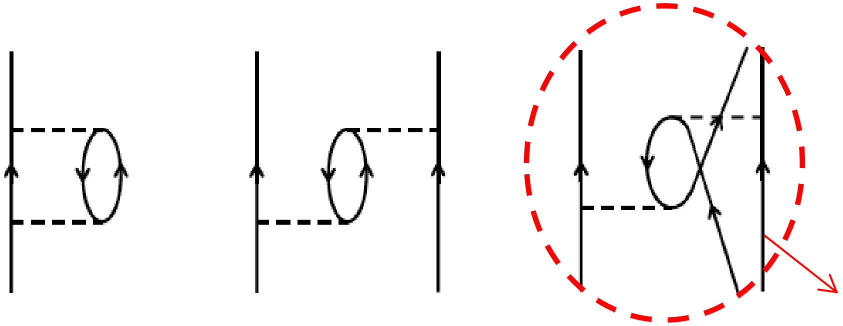
- - - $g_{9/2}$

-·-· $g_{9/2}^{(n-1)}$ + ν shells above

······ $g_{9/2}^{(n-1)}$ + ν shells above + core exc.

Kahana Lee Scott (KLS) interaction

S. Kahana, Scott, Lee Phys. Rev. 185 (1969).
A. Abzouzi, E. Caurier, and A.P. Zuker, Phys. Rev. Lett. **66**, 1134,(1991).
M. Dufour and A.P. Zuker PRC54 1641 (1996)



One body **Two body** **Three body**

Usually neglected!

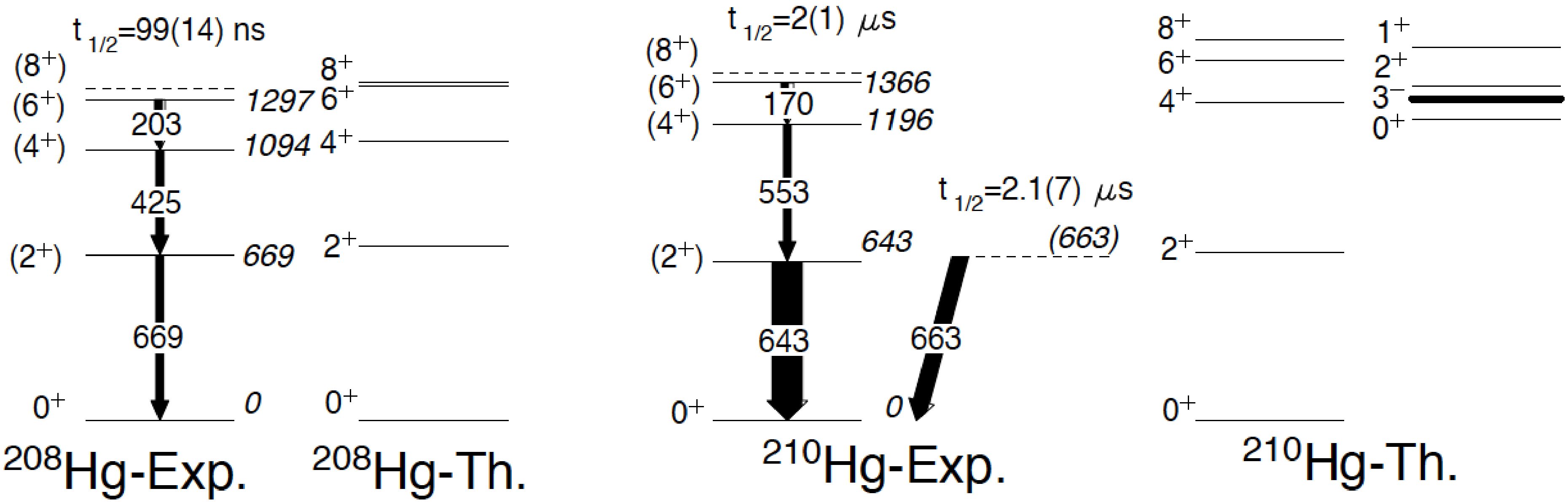
Standard eff. charges:

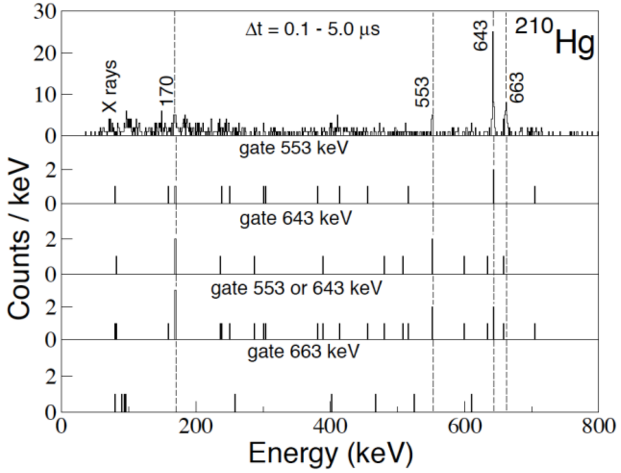
$e_\nu = 0.5$, $e_\pi = 1.5$

The explicit coupling to the core restores the conjugation symmetry

A. Gottardo et al., PRL109, 162502 (2012)

Bi-isomer in ^{210}Hg





E3 (663keV) and E1 (20 keV)
10^6 suppression in the E1

Such a large drop of the 3- excitation in ^{210}Hg, if proven by more sophisticated and high statistics experiments, will be a real challenge for present theoretical models: ad augusta per angusta .

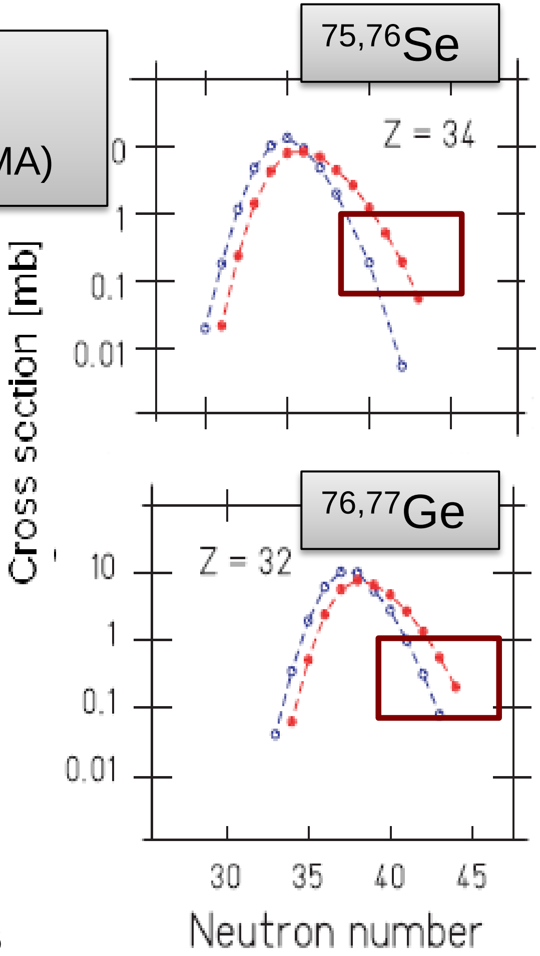
A. Gottardo et al., PLB (submitted)

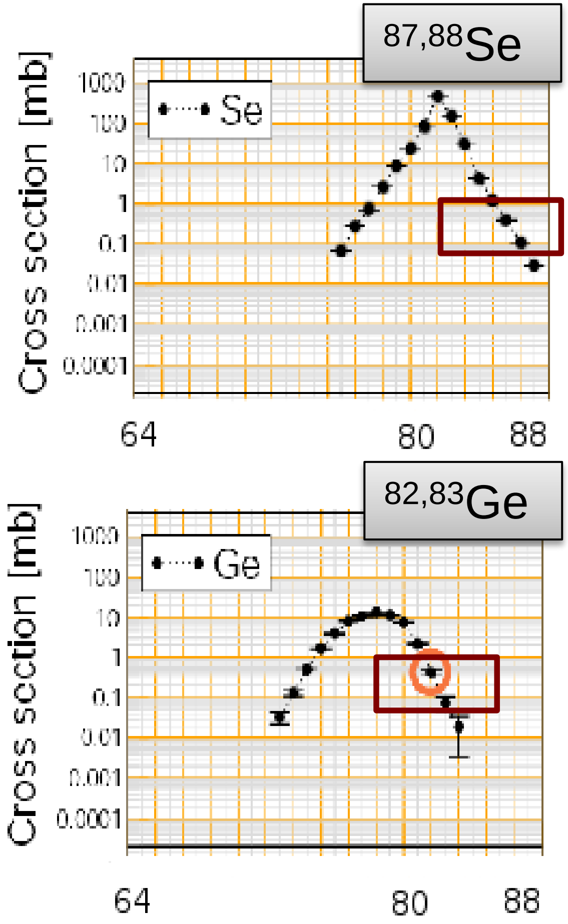
Fragmentation vs. MNT

- Fragmentation reactions of Xe isotopes at 1 A GeV on heavy targets
- Multinucleon transfer reactions (higher spins)

Red: 136Xe+Pb (fragmentation)
Blue 124Xe+Pb (fragmentation)
Black: 82Se+238U (MNT - PRISMA)

In fragmentation reactions (fragment separator (FRS) of GSI) on heavy targets one gets strongly decreasing yields (of medium mass neutron rich isotopes), due to secondary processes



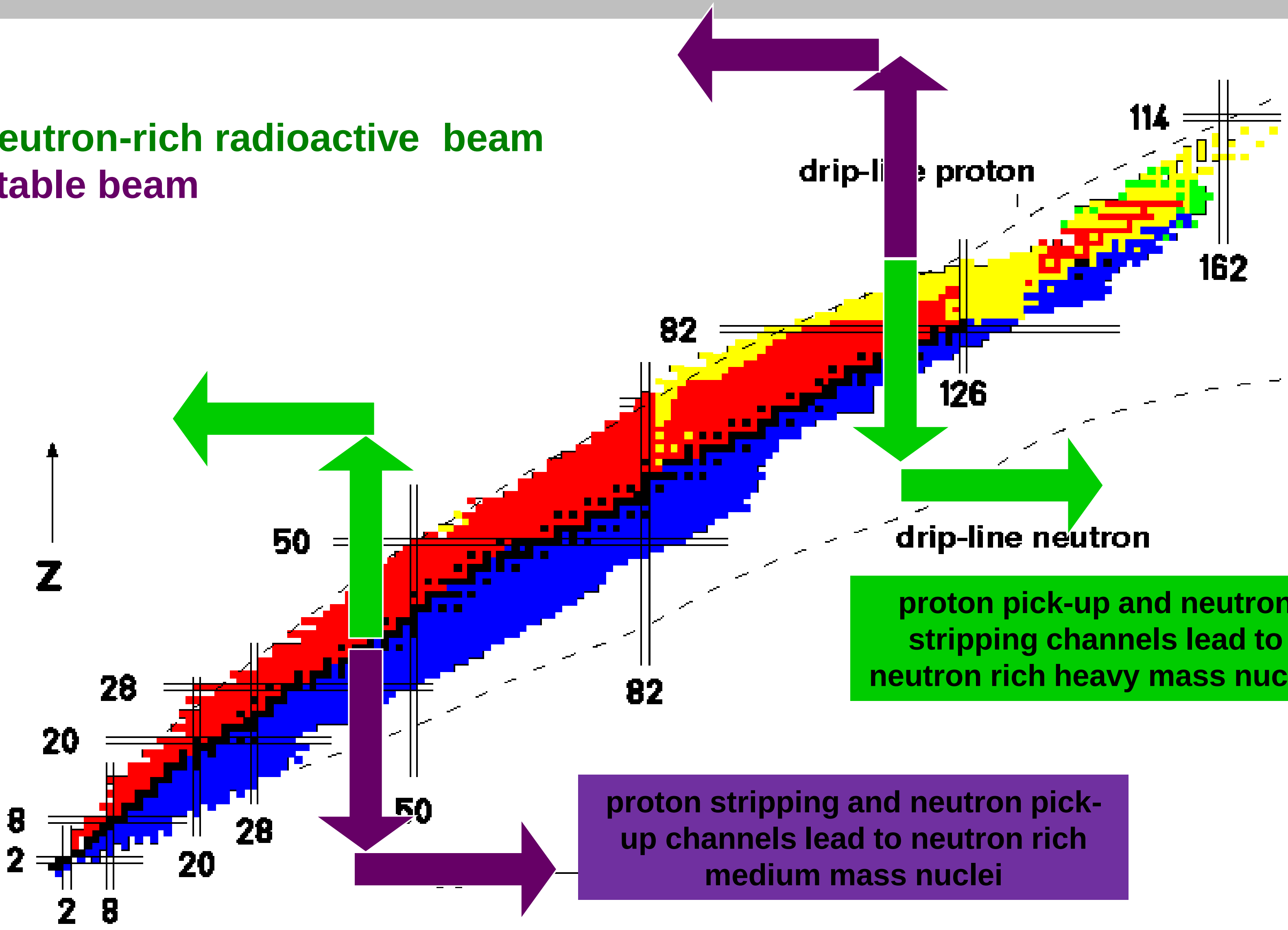


D. Henzlova et al, PRC78(2008)044616

Multinucleon transfer reactions RIB

Neutron-rich radioactive beam

Stable beam



proton pick-up and neutron stripping channels lead to neutron rich heavy mass nuclei

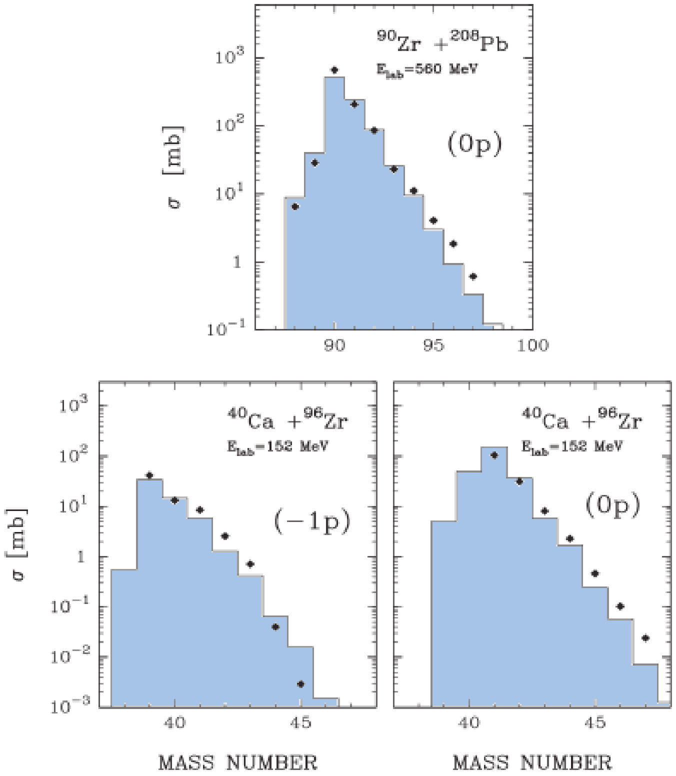
proton stripping and neutron pick-up channels lead to neutron rich medium mass nuclei

C.H.Dasso, G.Pollarolo, A.Winther, PRL73 (1994)1907

GRAZING calculations

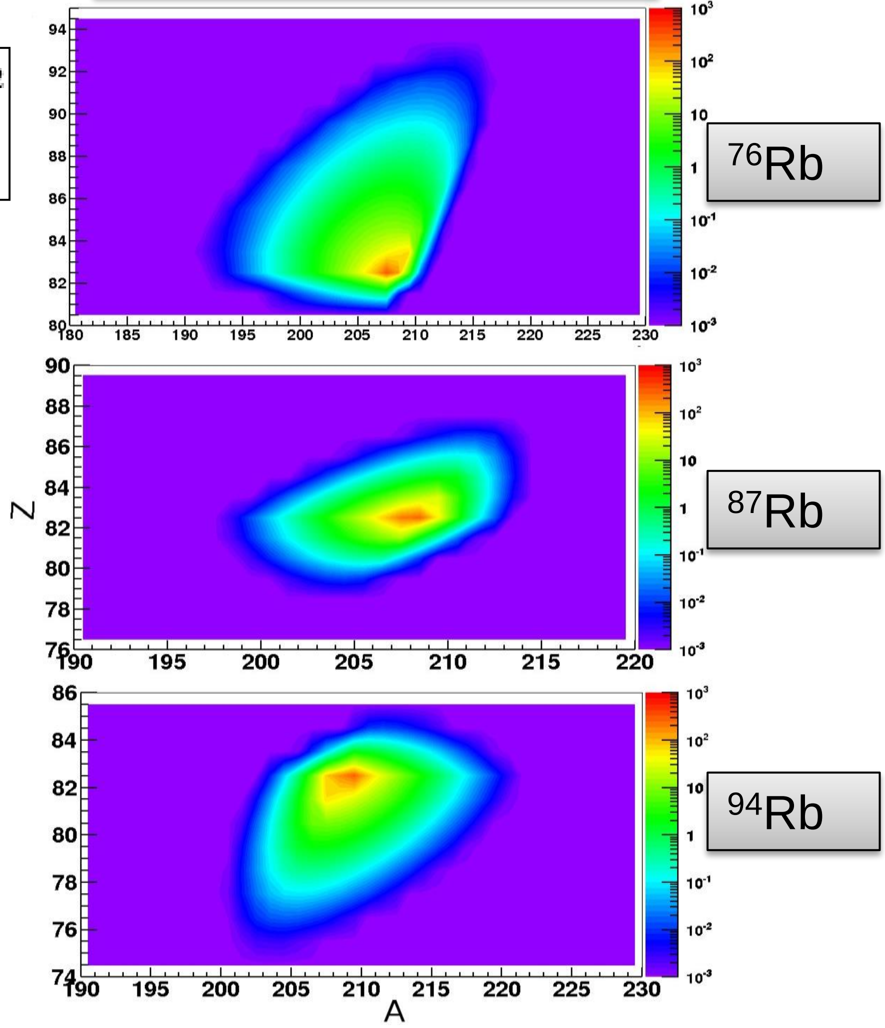
Semiclassical theory (Grazing)
G.Pollarolo, A.Winther

$$P_{\beta\alpha}(\ell) = \left| \frac{\mathrm{i}}{\hbar} \int_{-\infty}^{+\infty} \mathrm{d}t\, \mathrm{e}^{\mathrm{i}\sigma_{\beta\alpha}t}\, f_{\beta\alpha}(0,\vec{r})\, \mathrm{e}^{\mathrm{i}[(E_\beta - E_\alpha)+(\delta_\beta-\delta_\alpha)]t/\hbar} \right|^2$$



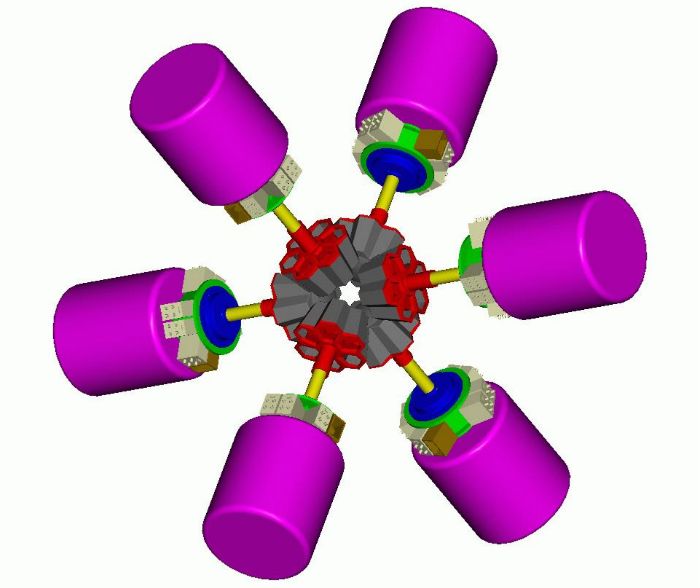
S. Szilner et al., PRC76 024604 (2007)

Distribution of Pb-like

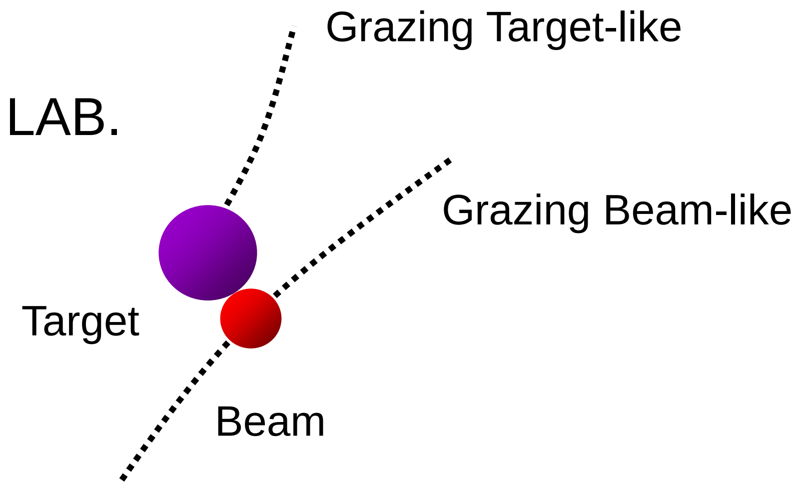


Experimental details

MNT to populate ^{212,214}Pb and ^{210}Hg among others



- Beam of ^{94}Rb 5.5 MeV/u (HIE-ISOLDE)
- Current: 2 10^{8} at/μC (UCx) – 1.5 10^{7} pps at MINIBALL (transmission eff. 5%)
- 13 mg/cm^{2} ^{208}Pb target
- MINIBALL
- 9-gap amplifier a 1.5 ms pulse width
- Trigger gamma-gamma
- Background substraction between pulses (W. Catford et al., NPA616 303 (1997))

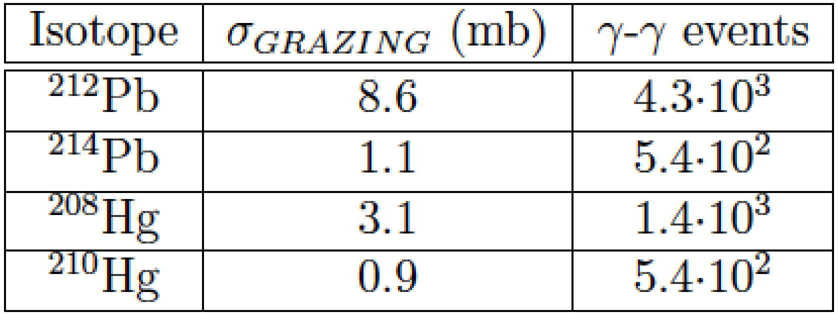


Straggling and Rutherford scattering contribute to a singles gamma rate at the secular equilibrium up to around 1 kHz

The beam will be stopped in a beam dump outside MINIBALL well shielded to avoid background in the HPGe detectors.

Beam time request

- Considering a gamma eff. of 6.0% for MINIBALL
- An effective thickness of 4.0 mg/cm^2 of ^{208}Pb
- Due to secondary processes the yields can be reduced up to a factor of 5.



Isotope	$\sigma_{GRAZING}$ (mb)	γ-γ events
^{212}Pb	8.6	$4.3 \cdot 10^3$
^{214}Pb	1.1	$5.4 \cdot 10^2$
^{208}Hg	3.1	$1.4 \cdot 10^3$
^{210}Hg	0.9	$5.4 \cdot 10^2$

Considering this scenario we request 9 days of beam time including 1 day for setup. **Total 9 days**

Collaboration

J.J. Valiente-Dobón[1], S. Szilner[2], D. Bazzacco[3], G. Benzoni[11], S. Bottoni[11], A. Blazhev[8], M.J.G. Borge[5,9], A. Bracco[11], R. Carroll[12], L. Corradi[1], F. Crespi[11], T. Daniel[12], G. de Angelis[1], H. Duckwitz[8], E. Fioretto[1], F. Flavigny[4], C. Fransen[8], A. Gadea[7], A. Gottardo[1], R. Gernhäuser[6], L. Gurgi[12], M. Huyse[4], T. Hüyük[7], A. Illana Sisón[9], D. Jelavić Malenica[2], P. R. John[3], A. Jungclaus[9], Th. Kröll[10], R. Krücken[13] S. Lenzi[3], S. Leoni[11], S. Lunardi[3], M. Milin[2], R. Menegazzo[3], D. Mengoni[3], C. Michelagnoli[3], T. Mijatović[2], V. Modamio[1], G. Montagnoli[3], D. Montanari[3], D. Mücher[6], D.R. Napoli[1], K. Nowak[6], R. Orlandi[4], Z. Patel[12], R.M. Perez-Vidal[7], Zs. Podolyak[12], R. Raabe[4], G. Randisi[4], E. Rapisarda[5], P. Regan[12], P. Reiter[8], C. Shand[12], A. Stefanini[1], T. Stora[5], P. Van Duppen[4], C.A. Ur[3], D. Voulot[5], N. Warr[8], F.K. Wenander[5]

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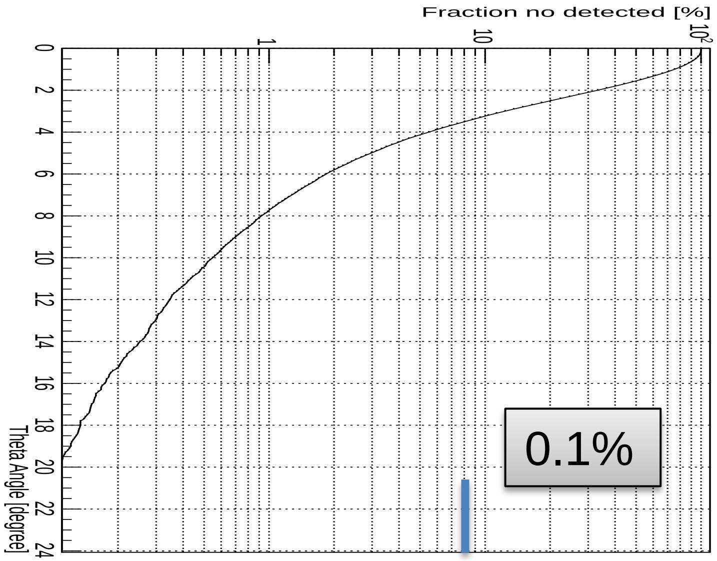
Straggling + Rutherford

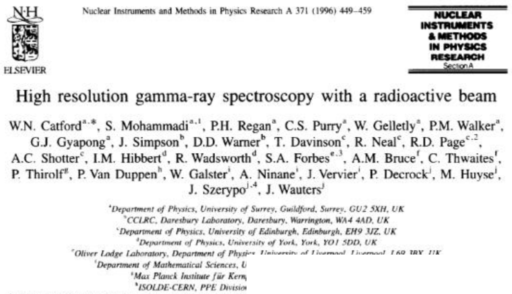


0.1%

Let's say that at the secular equilibrium we have 0.1% of 1.5 10^7 pps = 1.5 10^4 pps x 2 (average gamma multiplicity) x 0.003 (efficiency of 1 crystal) = 90 Hz. Therefore, this contribution is negligible to the germanium counting.

For the **Rutherford scattering**, the upper limit of cross section for angles beyond 15 degrees (opening of the reaction chamber) is approximately, for the lowest possible energy at the exit of the target (to take the upper limit), is 0.3 10^6 mb and this gives a counting rate in singles of around 1 KHz. This does not represent a problem. For the trigger, gamma-gamma, this contribution is negligible.

Time background substraction



ELSEVIER

Nuclear Instruments and Methods in Physics Research A 371 (1996) 449–459

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

High resolution gamma-ray spectroscopy with a radioactive beam

W.N. Catford[a,*], S. Mohammadi[a,1], P.H. Regan[a], C.S. Purry[a], W. Gelletly[a], P.M. Walker[a], G.J. Gyapong[a], J. Simpson[b], D.D. Warner[b], T. Davinson[c], R. Neal[c], R.D. Page[c,2], A.C. Shotter[c], I.M. Hibbert[d], R. Wadsworth[d], S.A. Forbes[e,3], A.M. Bruce[f], C. Thwaites[f], P. Thirolf[g], P. Van Duppen[h], W. Galster[i], A. Ninane[i], J. Vervier[i], P. Decrock[j], M. Huyse[j], J. Szerypo[j,4], J. Wauters[j]

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B
[j]Instituut voor Kern- en Stralingsfysica, Kath

Received 7

Abstract

The γ-rays de-exciting the yrast states in neutron def
evaporation reactions induced by an intense radioactive
germanium detectors recorded reaction γ-rays. Background
using the timing properties of the pulsed beam and through
data constitute the first use of an on line separated and acc
using fusion-evaporation reactions. Information on the γ-ray
beam, has been obtained and the problems associated with
environment have been addressed.

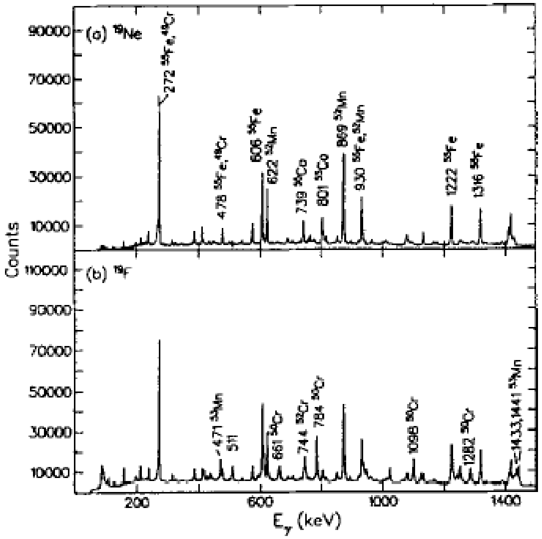


Figure 2. Comparison between (a) the background-subtracted singles spectrum with the radioactive ^{19}Ne beam, and (b) the singles spectrum with the stable ^{19}F beam.

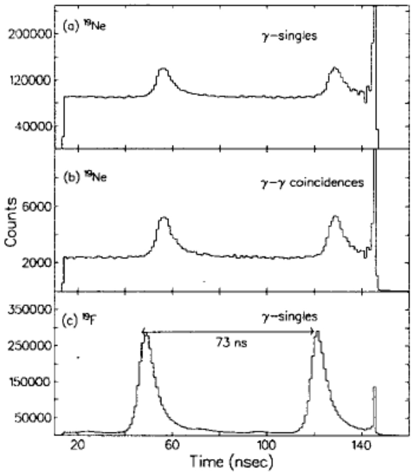
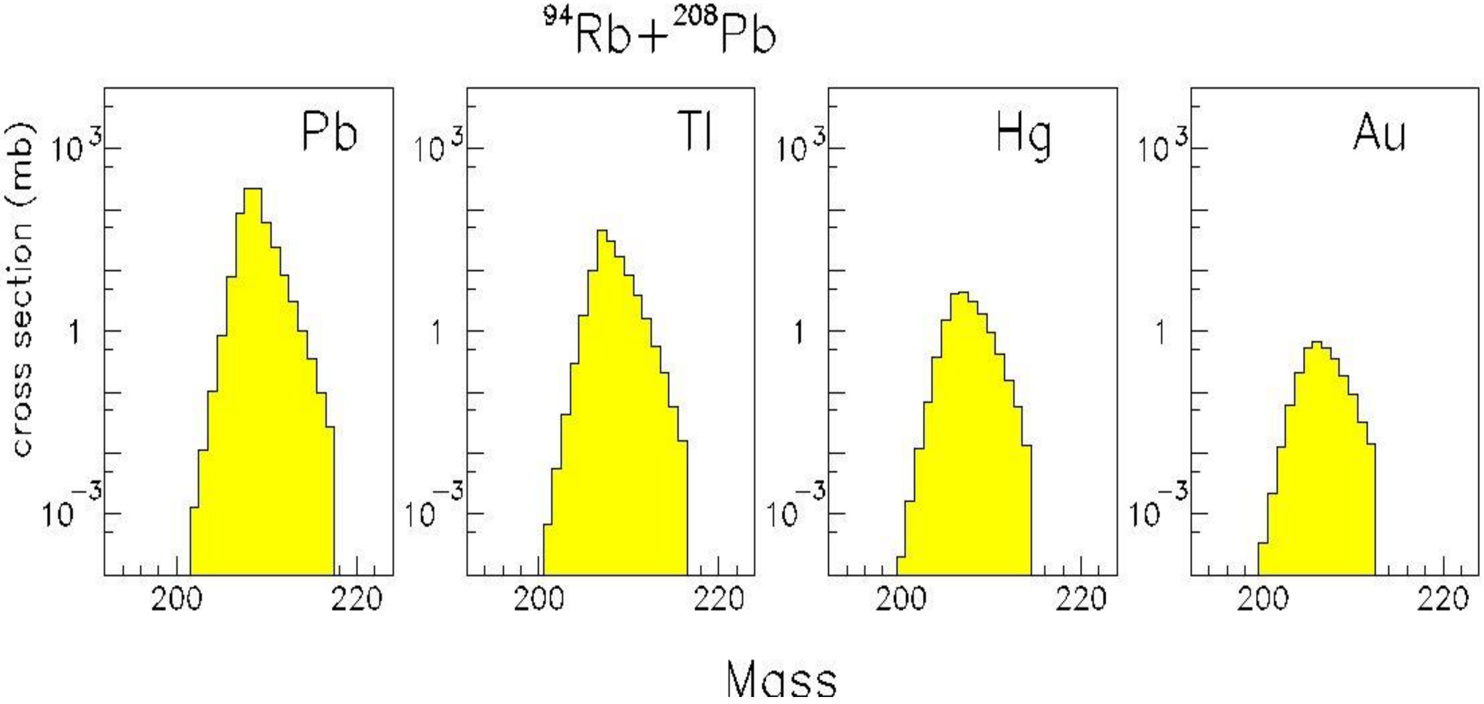


Figure 1. Times of gamma-ray events measured relative to the beam pulses (which correspond to the peaks): (a) singles with ^{19}Ne beam, (b) gamma-gamma coincidences with ^{19}Ne beam, and (c) singles with ^{19}F beam. For technical reasons, the beam pulse events are divided between two peaks in the spectra.

GRAZING



Optimum Q value and adiabatic cut-off function

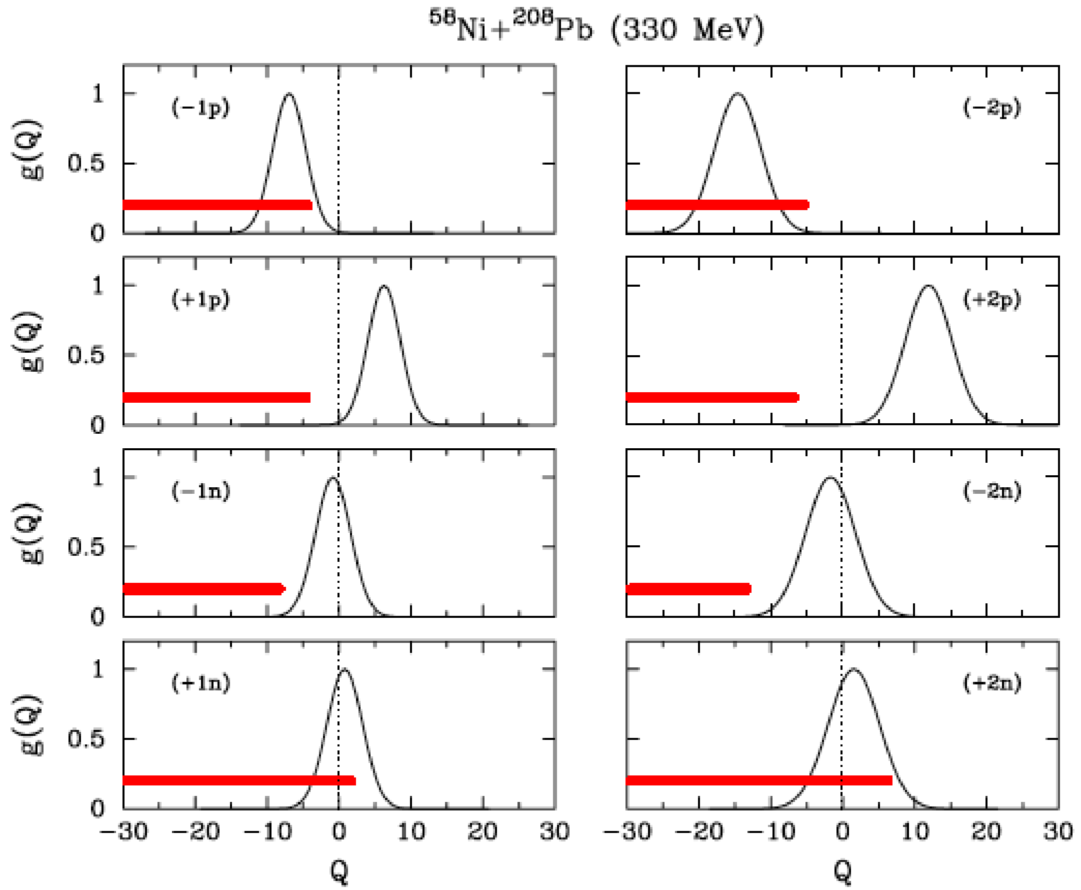
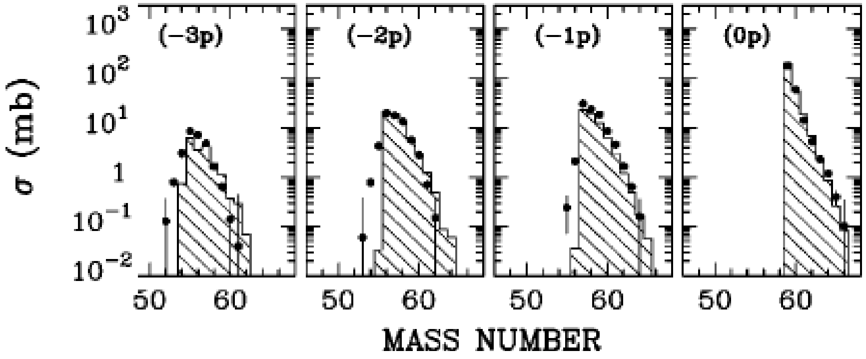


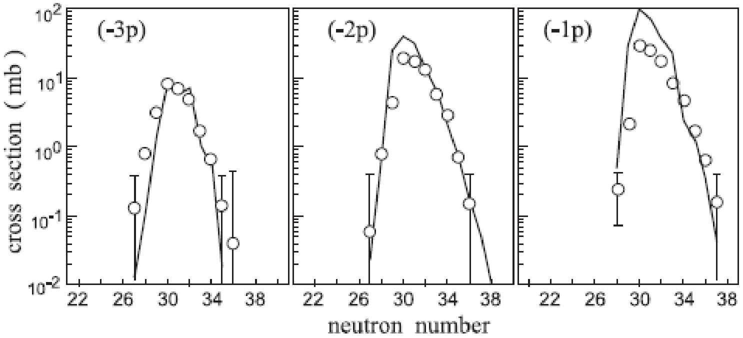
Figure 6. Adiabatic cut-off functions for one- and two-neutron and proton transfer channels for the reaction ^{58}Ni+^{208}Pb at the indicated energy (Q-value in MeV). The horizontal lines represent the location of all possible transitions.

MNT: experiment vs. theory



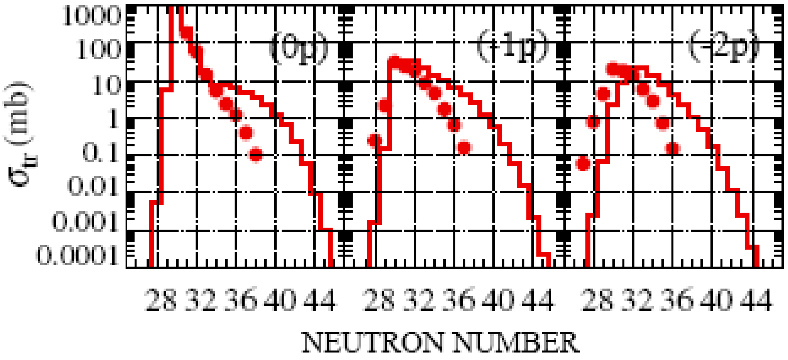
Semiclassical theory (Grazing,CWKB)
G.Pollarolo, A.Winther

$$P_{\beta\alpha}(\ell) = \left| \frac{\mathrm{i}}{\hbar} \int_{-\infty}^{+\infty} \mathrm{d}t\, \mathrm{e}^{\mathrm{i}\sigma_{\beta\alpha} t} f_{\beta\alpha}(0,\vec{r})\, \mathrm{e}^{\mathrm{i}[(E_\beta - E_\alpha)+(\delta_\beta-\delta_\alpha)]t/\hbar} \right|^2$$



Langevin equations
V.Zagrebaev, W.Greiner

$$\frac{d\eta_N}{dt} = \frac{2}{N_{\mathrm{CN}}} D_N^{(1)} + \frac{2}{N_{\mathrm{CN}}}\sqrt{D_N^{(2)}}\,\Gamma_N(t),$$

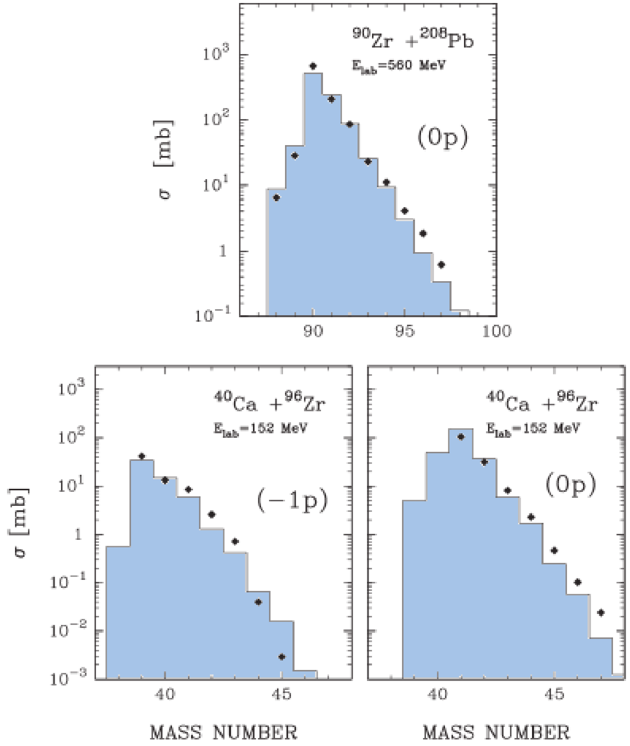


Time Dependent Hartree-Fock theory
Yabana

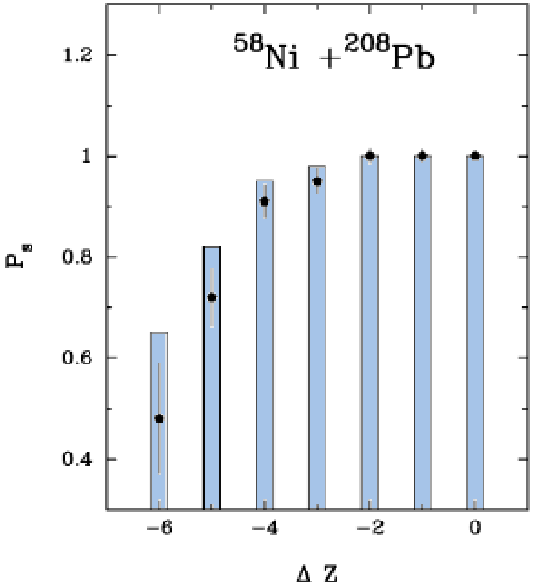
$$P_n = \int dx_1 \cdots \int dx_N\, \psi_1^*(x_1)\cdots\psi_N^*(x_N)\hat{P}_n \det\{\psi_i(x_j)\}$$

comparison with 58Ni+208Pb data, L.Corradi et al PRC66(2002)024606

MNT: experiment vs. theory

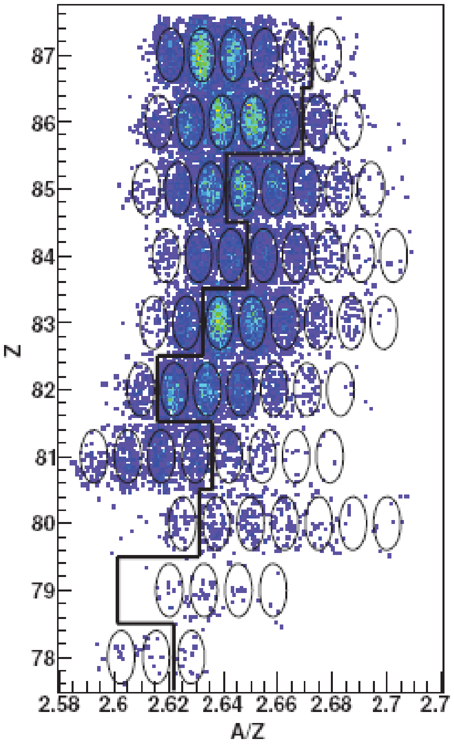


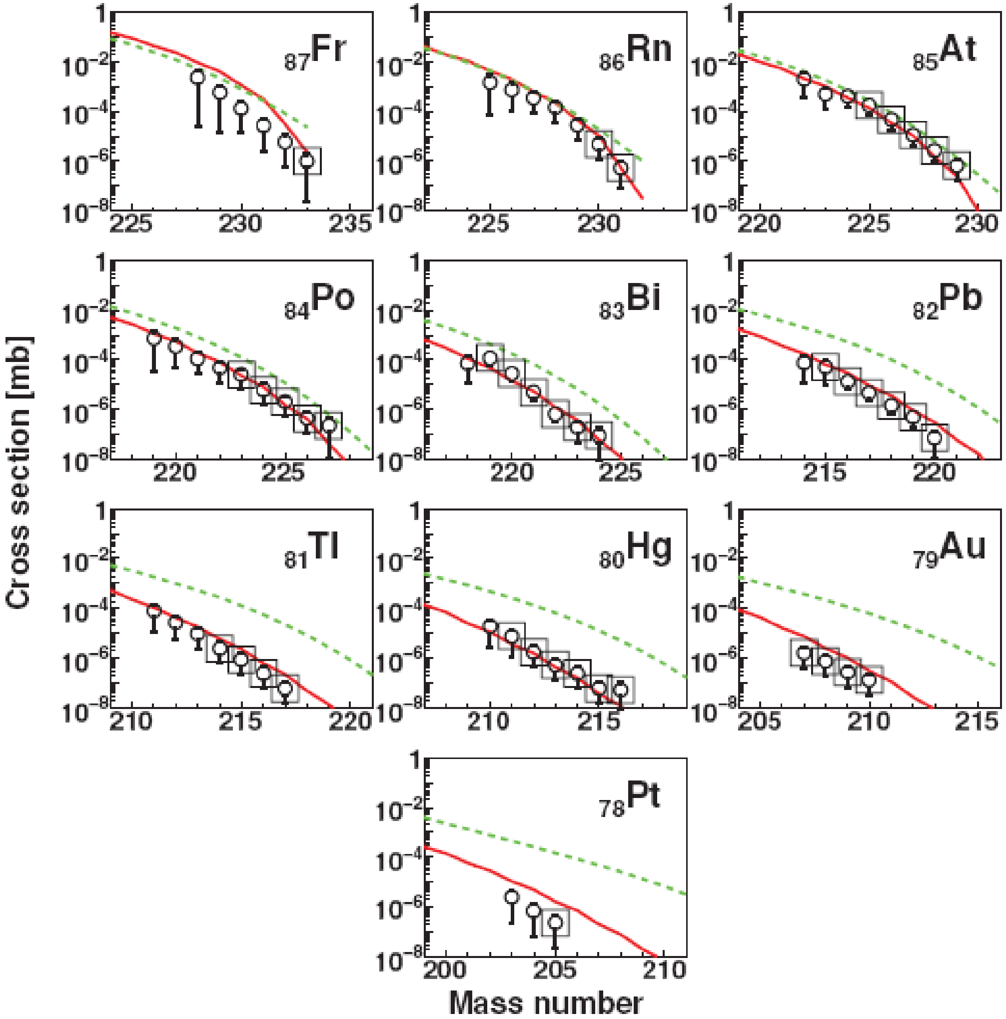
- Total cross sections for pure neutron pick-up
- channels in the 90Zr+208Pb reaction.
- Total cross sections for pure neutron pick-up (right panel) and one-proton stripping (left panel) channels in the 40Ca+96Zr reaction.
- The points are the experimental data and the histograms are the calculated by GRAZING code.
- S. Szilner et al, Phy. Rev. C 76, 024604 (2007)



- Survival probability against fission (Ps)
- for the heavy
- target-like fragments as a function of the number of transferred protons
- averaged over neutron
- numbers. Points and histograms are the experimental and theoretical GRAZING values, respectively.
- L. Corradi et al, PRC 66, 024606 (2002).

Fragmentation reactions of 238U at 1 A GeV on Be targets



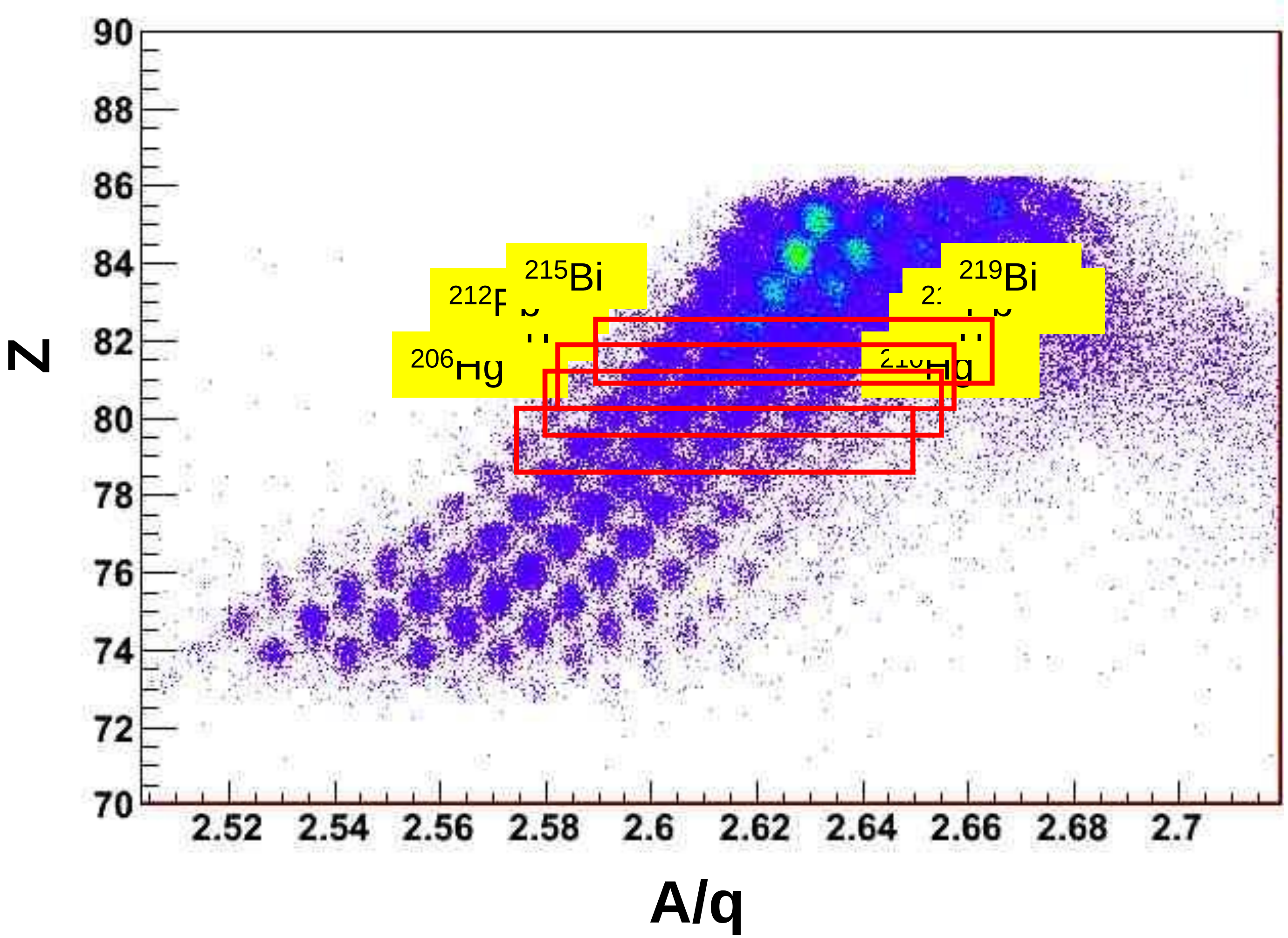


In fragmentation reactions on light targets one could produce very neutron rich nuclei in the “northeast” region, with cross sections down to 100 pb

H.Alvarez-Pol et al, Phys.Rev.C82(2010)041602R

Fragmentation reactions

1 GeVA ^{238}U beam from UNILAC-SIS at 10^9 pps



Wave functions from Kuo-Herling

The neutron $2g_{9/2}$ shell has a dominant role for the 8^+ isomeric state.
$1i_{11/2}$, $1j_{15/2}$ and $3d_{5/2}$ also play a role

8^+ state wave functions: occupational numbers show quite pure wave functions

	^{210}Pb n = 2	^{212}Pb n = 4	^{214}Pb n = 6	^{216}Pb n = 8	^{218}Pb n = 10
$2g_{9/2}$	1.99	3.39	4.78	6.21	6.96
$1i_{11/2}$	0.005	0.33	0.68	1.04	2.16
$1j_{15/2}$	0.002	0.16	0.32	0.43	0.59
$3d_{5/2}$	0.0008	0.04	0.08	0.11	0.14

Occupational numbers

The ground state wave functions are in general more fragmented, with the $1i_{11/2}$ shell around 25 - 30 %

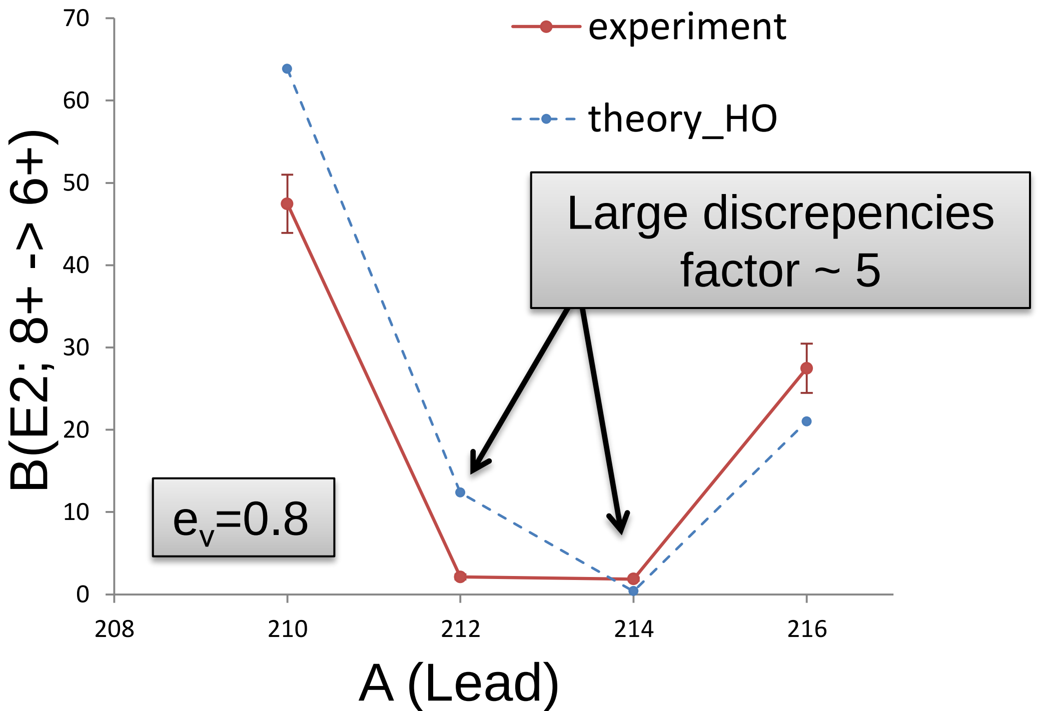
Reduced transition prob. B(E2)

B(E2) calculated considering internal conversion coefficients, and a 20-90 keV energy interval for unknown transitions.

	^{210}Pb	^{212}Pb	^{214}Pb	^{216}Pb
Isomer $t_{1/2}$ (μs)	**0.20 (2)**	**6.0 (8)**	**6.2 (3)**	**0.40 (4)**
B(E2) e^2fm^4 Exp.	**47(4)**	**1.8(3)**	**1.4-1.9**	**24.7-30.5**
B(E2) e^2fm^4 KH	**41**	**8**	**0.26**	**16.4**

Upper limit 90 keV based on K_α X rays intensity (K electrons bound ~88 keV)

$$B(E2) \sim E_\gamma^{-5}\,(1+\alpha)^{-1}\tau^{-1}$$



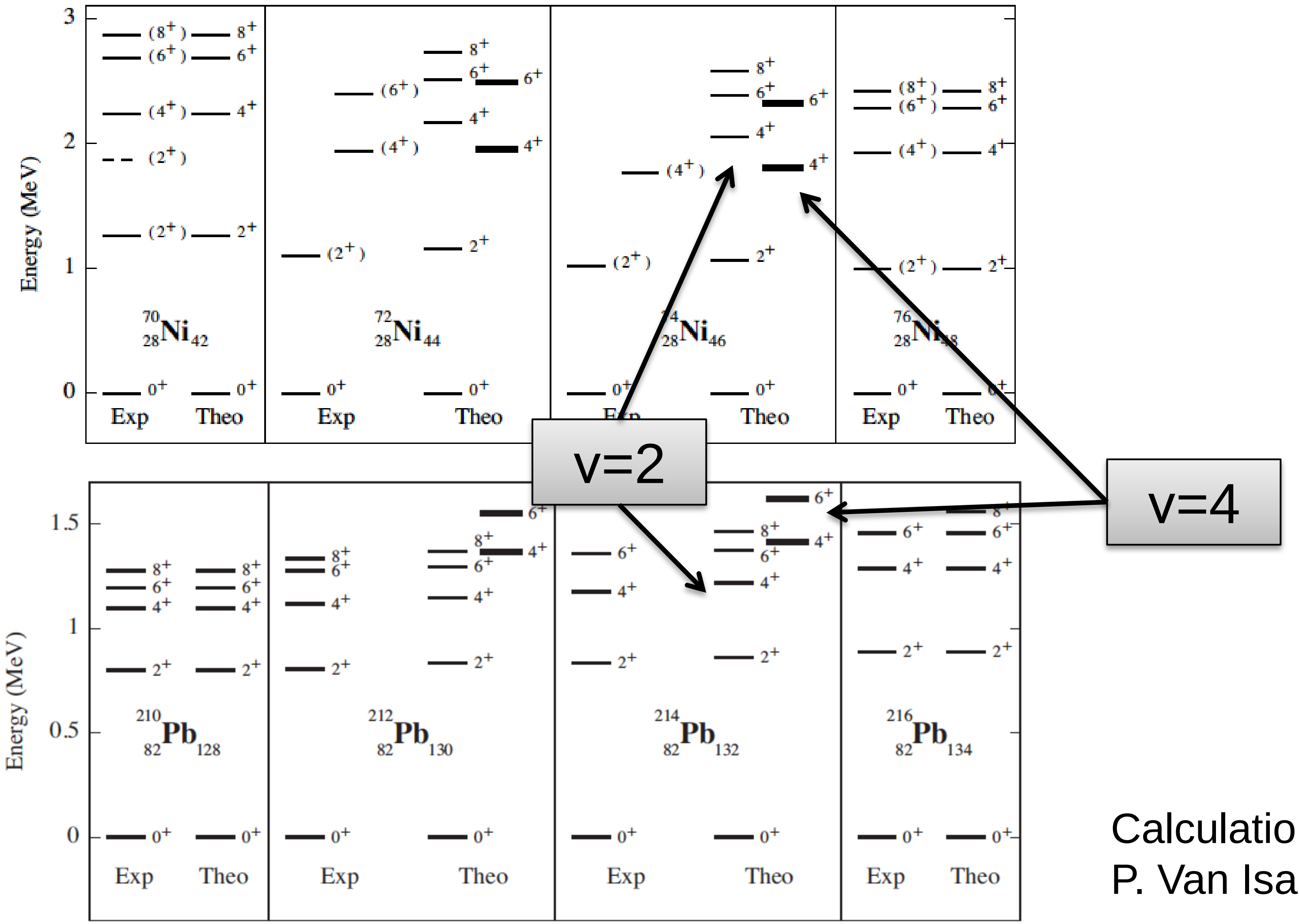
Large discrepencies factor ~ 5

$e_v=0.8$

Origin of discrepancies

- The results are roughly independent of the interaction used: KH, CD-Bonn, etc.
- One possibility is the mixing of states 6^+ with different seniorites, but requires too large change of the realistic interaction → Is not the case
- Seniority mixing with $g_{9/2}$ seniority isomers also for the first $g_{9/2}$ (neutrons: ^{70}Ni - ^{76}Ni, protons: ^{92}Mo - ^{98}Cd)

Seniority Mixing



v=2

v=4

Calculations by
P. Van Isacker

Origin of discrepancies

- The results are roughly independent of the interaction used: KH, CD-Bonn, Delta, Gaussian
- One possibility is the mixing of states 6^+ with different seniorites, but requires too large change of the realistic interaction → Is not the case
- Seniority mixing with $g_{9/2}$ seniority isomers also for the first $g_{9/2}$ (neutrons: ^{70}Ni - ^{76}Ni, protons: ^{92}Mo - ^{98}Cd)

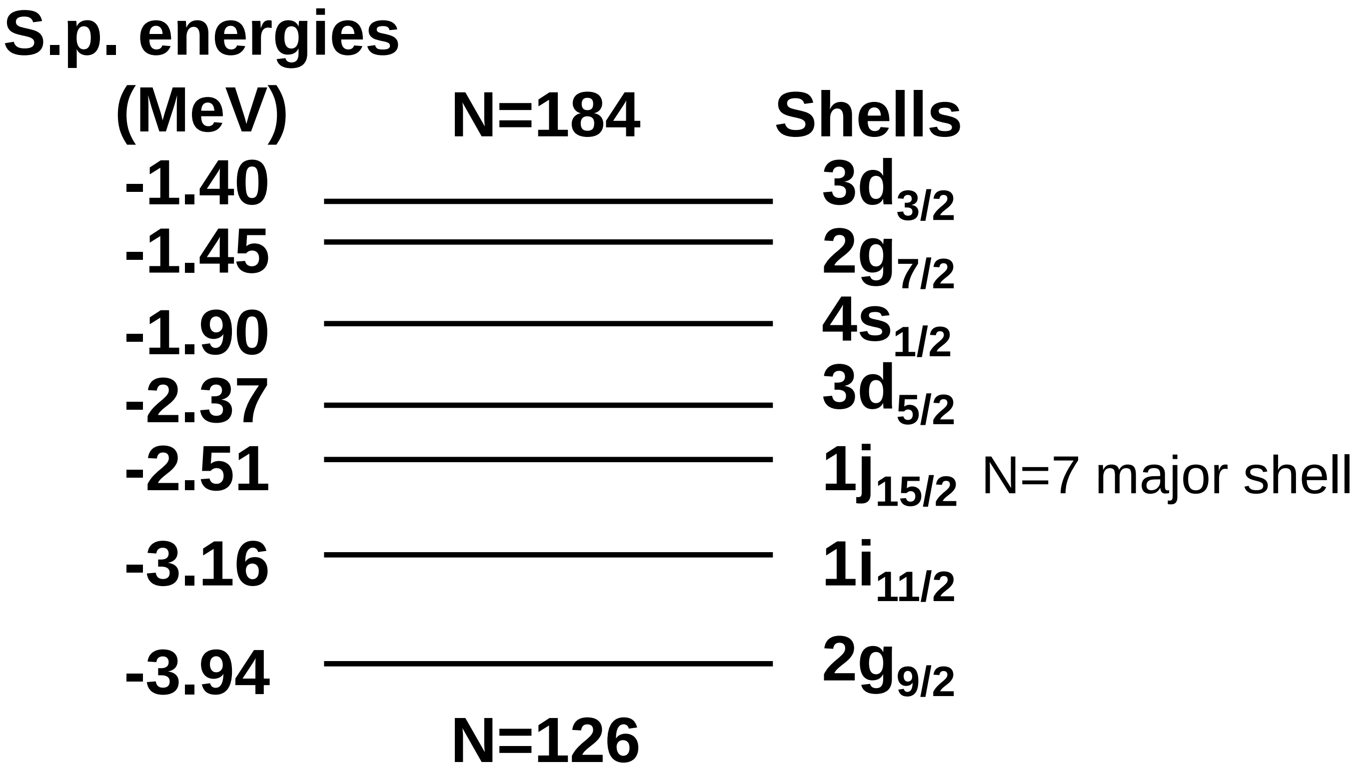
So …..

- Need to introduce state-dependent effective charges?
- Caution when using renormalised interactions

Kuo-Herling interaction: Valence space

^{208}Pb is the core (Z=82, N=126).

- For neutron-rich Lead isotopes, the N=6 major shell is involved
- No shells beyond the magic numbers for neutrons

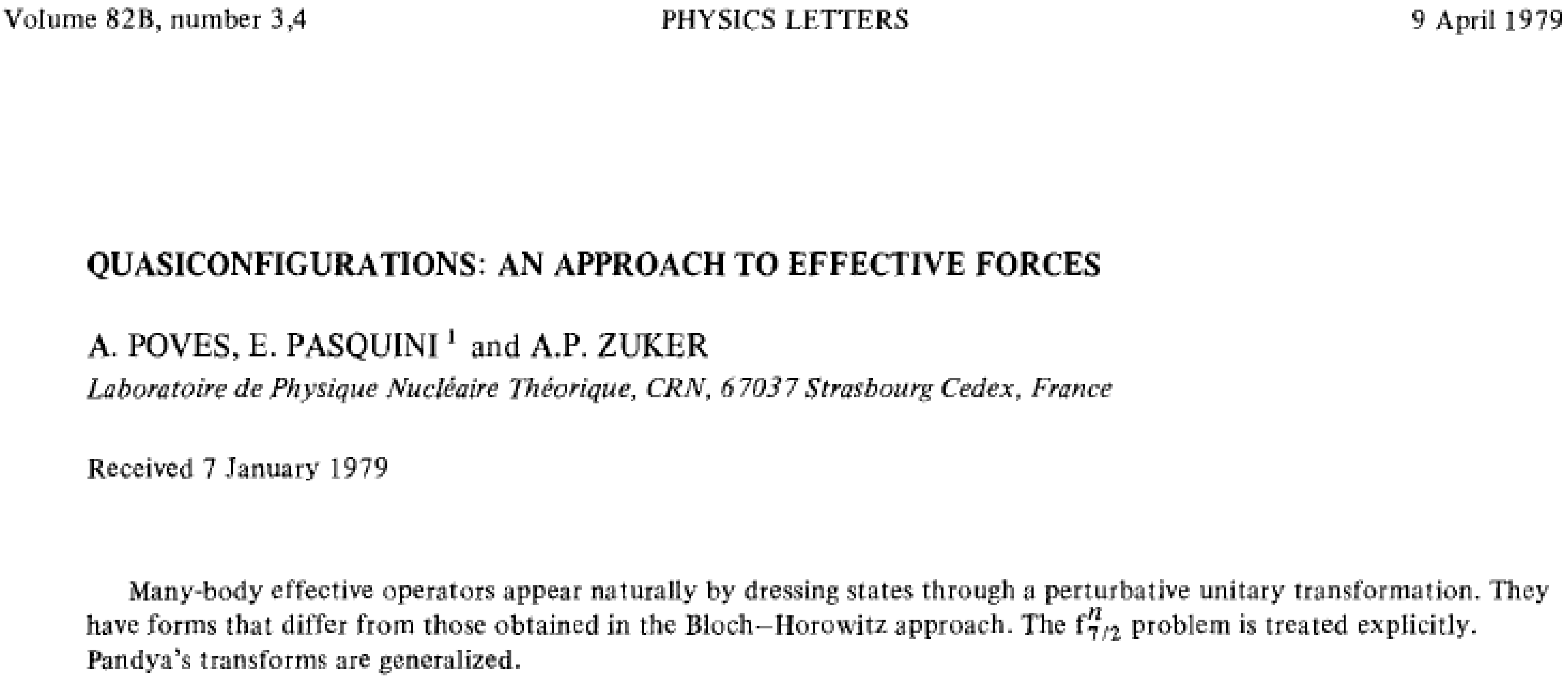


S.p. energies

(MeV)	**N=184**	**Shells**	
-1.40		**$3d_{3/2}$**	
-1.45		**$2g_{7/2}$**	
-1.90		**$4s_{1/2}$**	
-2.37		**$3d_{5/2}$**	
-2.51		**$1j_{15/2}$**	N=7 major shell
-3.16		**$1i_{11/2}$**	
-3.94		**$2g_{9/2}$**	
	N=126		

E.K. Warburton and B.A. Brown PRC43, 602 (1991).

Theory of effective interactions



Volume 82B, number 3,4 PHYSICS LETTERS 9 April 1979

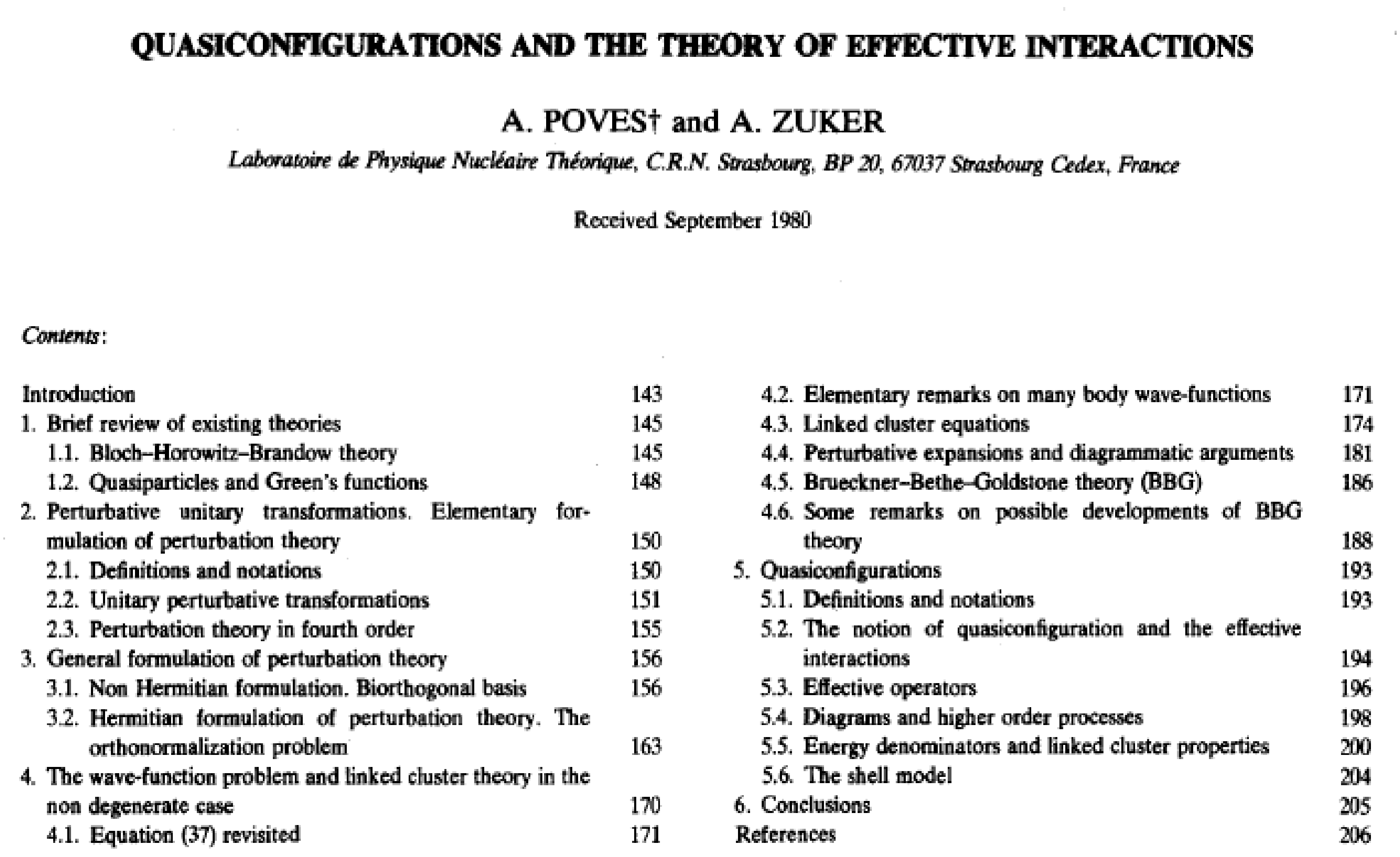
QUASICONFIGURATIONS: AN APPROACH TO EFFECTIVE FORCES

A. POVES, E. PASQUINI [1] and A.P. ZUKER
Laboratoire de Physique Nucléaire Théorique, CRN, 67037 Strasbourg Cedex, France

Received 7 January 1979

Many-body effective operators appear naturally by dressing states through a perturbative unitary transformation. They have forms that differ from those obtained in the Bloch–Horowitz approach. The $f_{7/2}^n$ problem is treated explicitly. Pandya's transforms are generalized.

Theory of effective interactions



QUASICONFIGURATIONS AND THE THEORY OF EFFECTIVE INTERACTIONS

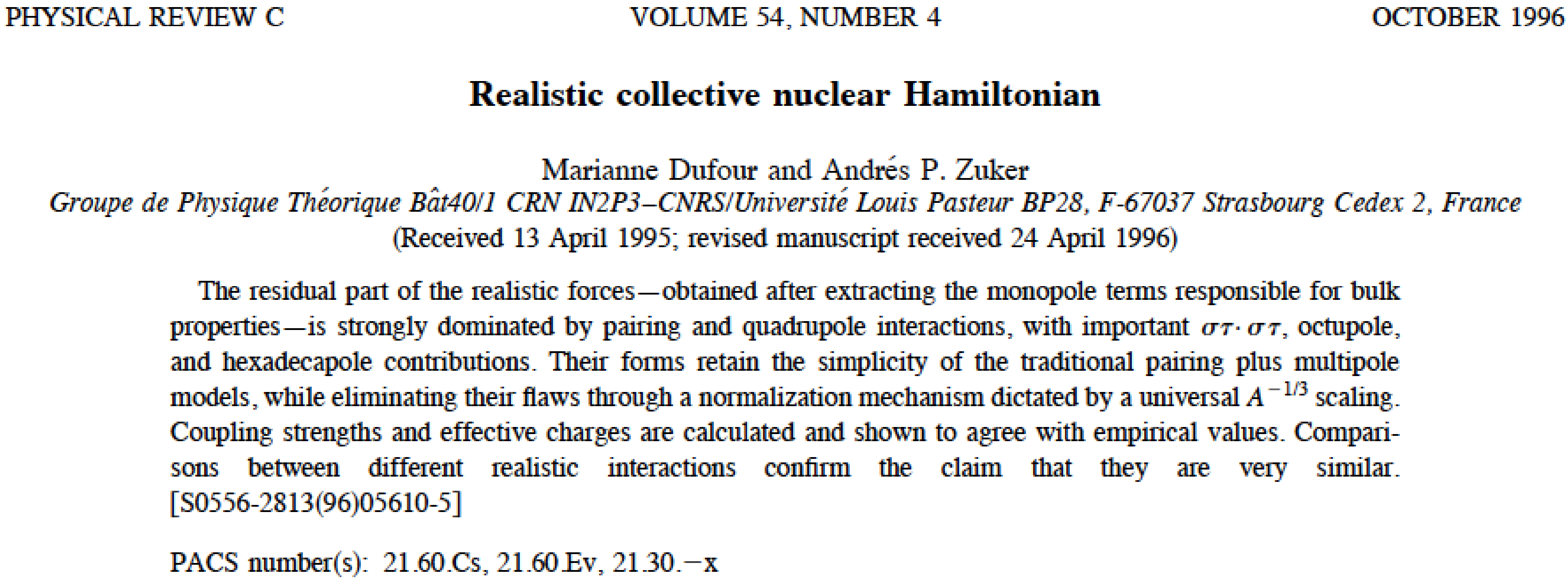
A. POVES† and A. ZUKER

Laboratoire de Physique Nucléaire Théorique, C.R.N. Strasbourg, BP 20, 67037 Strasbourg Cedex, France

Received September 1980

Contents:

Realistic collective nuclear H



PHYSICAL REVIEW C VOLUME 54, NUMBER 4 OCTOBER 1996

Realistic collective nuclear Hamiltonian

Marianne Dufour and Andrés P. Zuker
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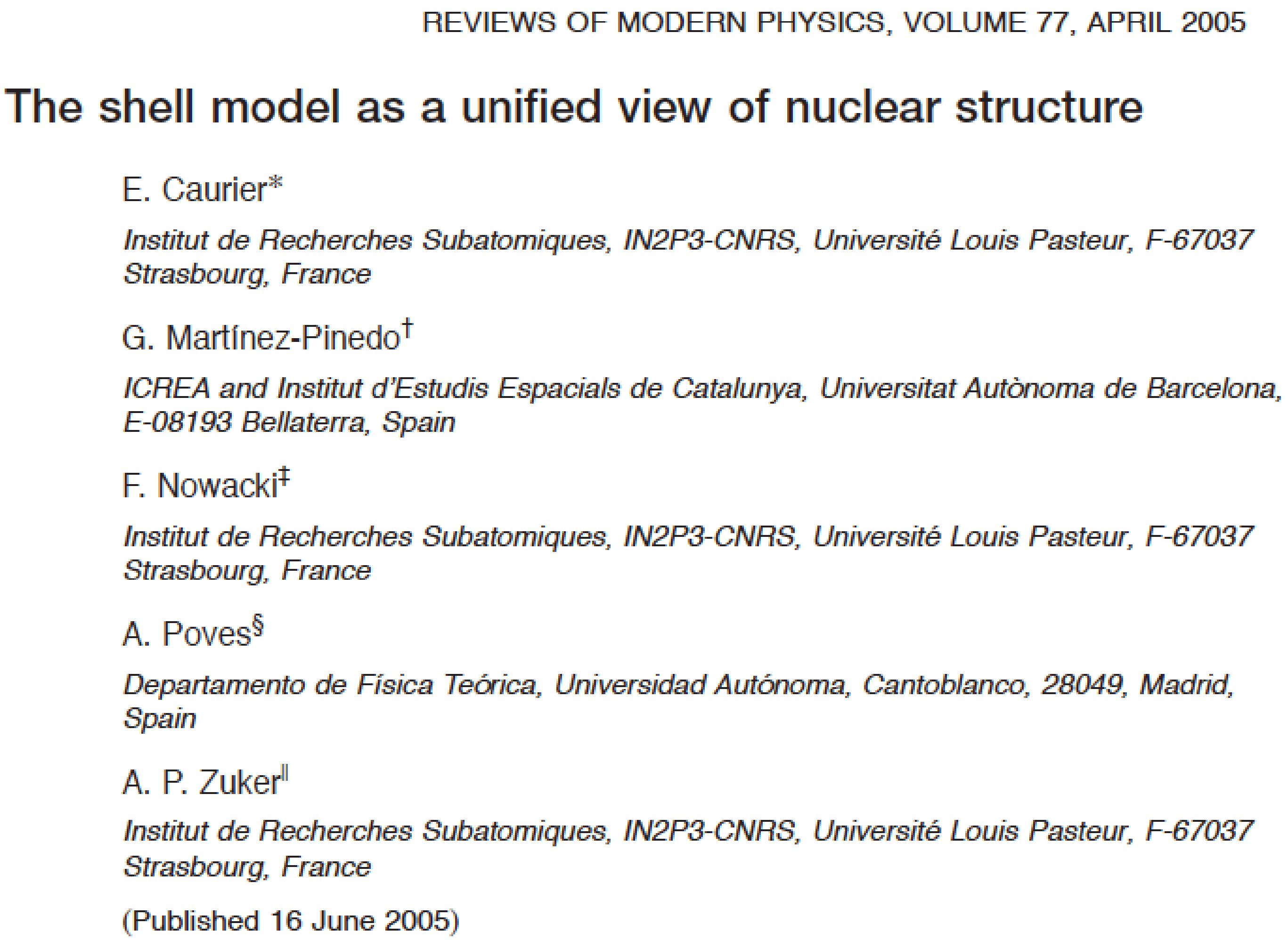
(Received 13 April 1995; revised manuscript received 24 April 1996)

The residual part of the realistic forces—obtained after extracting the monopole terms responsible for bulk properties—is strongly dominated by pairing and quadrupole interactions, with important $\sigma\tau\cdot\sigma\tau$, octupole, and hexadecapole contributions. Their forms retain the simplicity of the traditional pairing plus multipole models, while eliminating their flaws through a normalization mechanism dictated by a universal $A^{-1/3}$ scaling. Coupling strengths and effective charges are calculated and shown to agree with empirical values. Comparisons between different realistic interactions confirm the claim that they are very similar. [S0556-2813(96)05610-5]

PACS number(s): 21.60.Cs, 21.60.Ev, 21.30.−x

Unified view



REVIEWS OF MODERN PHYSICS, VOLUME 77, APRIL 2005

The shell model as a unified view of nuclear structure

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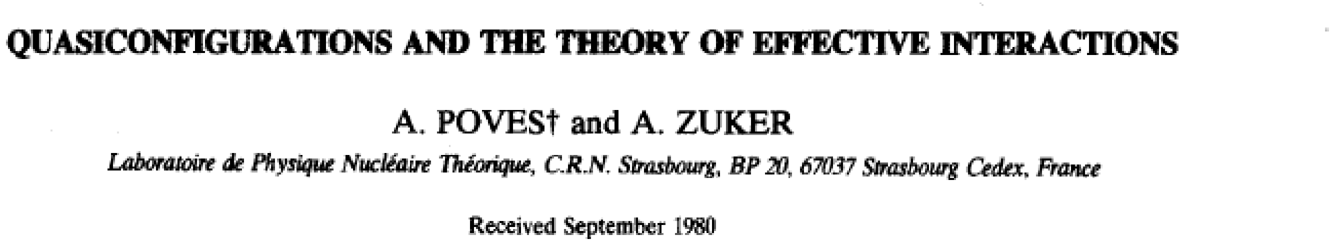
(Published 16 June 2005)

Effective 3 body interactions



QUASICONFIGURATIONS AND THE THEORY OF EFFECTIVE INTERACTIONS

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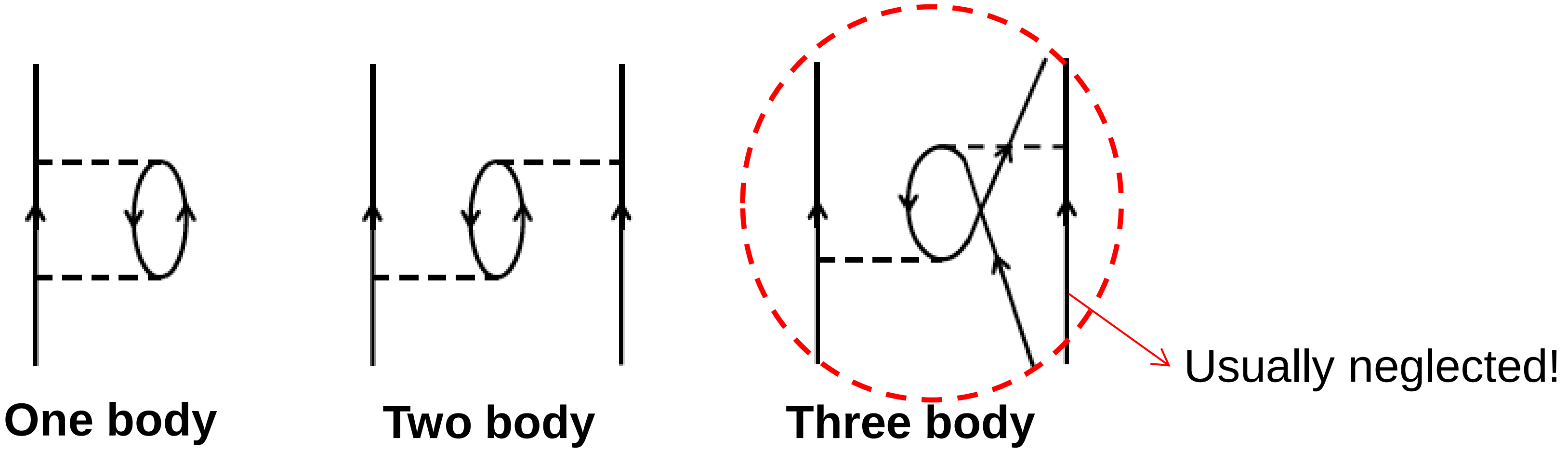
Received September 1980



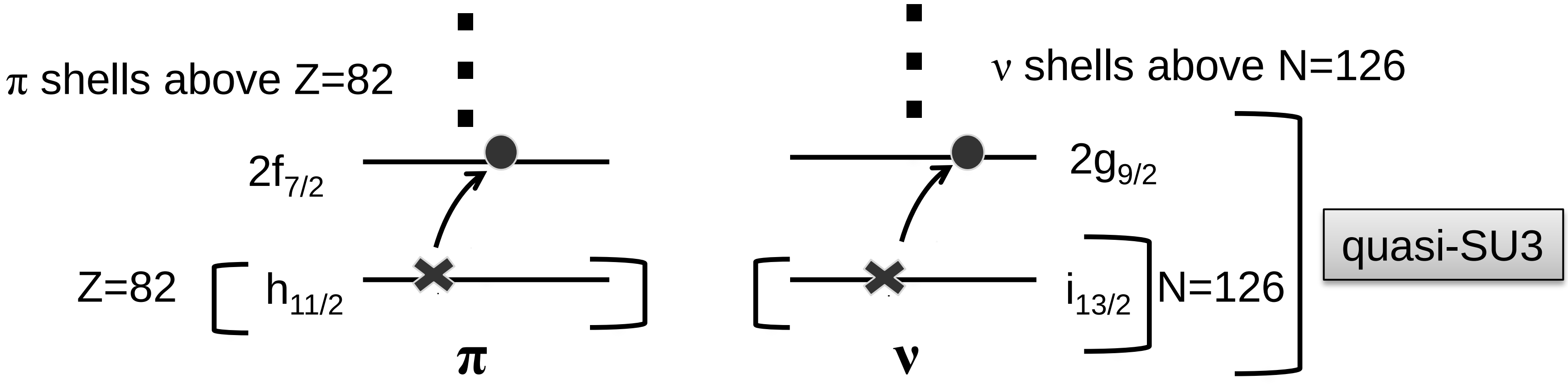
Effective 3-body terms appear naturally in the renormalization process, but they are NOT included in shell-model codes (ANTOINE and NATHAN):

- Two-body operators (H) become effective 3-body operators
- One-body transition operators (B(E2)) become effective 2-body operators

Effective three-body forces

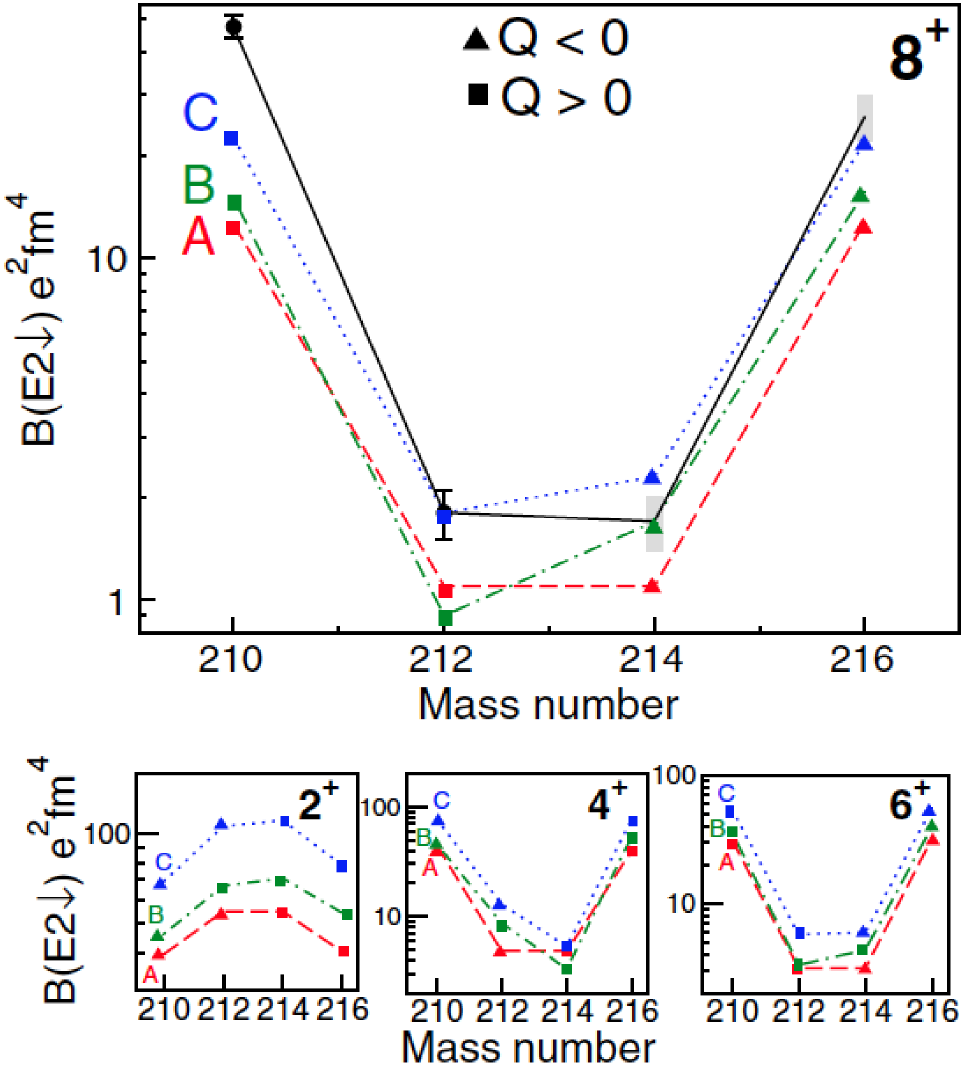
The only way to include in a standard shell-model calculation (ANTOINE, NATHAN) the effective 3-body force and 2-body operators is to diagonalize usign the dressed wave function. Expectation value of the Hamiltonian and of the transition operators is calculated directly between the dressed wave functions, thus also including the many-body terms otherwise neglected.

By allowing relevant p-h excitations from the core to the $g_{9/2}$ shell to neutron shells above, we include the previuosly neglected terms



In a perturbative approach, the bare $g_{9/2}$ is «dressed» with p-h excitations from the ^{208}Pb core

Effective 3-body interaction: Results



Exp. data

$g_{9/2}$

$g_{9/2}^{(n-1)}$ + $\boldsymbol{\nu}$ shells above

$g_{9/2}^{(n-1)}$ + $\boldsymbol{\nu}$ shells above + core exc.

Kahana Lee Scott (KLS) interaction

S. Kahana, Scott, Lee Phys. Rev. 185 (1969).
A. Abzouzi, E. Caurier, and A.P. Zuker, Phys. Rev. Lett. **66**, 1134,(1991).
M. Dufour and A.P. Zuker PRC54 1641 (1996)

Standard eff. charges:

$e_\nu = 0.5$, $e_\pi = 1.5$

The explicit coupling to the core restores the conjugation symmetry