F4E-SGA-168.01, Tasks 5.1/5.2
PN-II-ID-PCE-3-2011-0450

4th Workshop on Nuclear Level Density & Gamma Strength, Oslo, May 27-31,2013
[http://tid.uio.no/workshop2013/]

Radiative strength function low-energy enhancement within an Enhanced Generalized Lorentzian model

Vlad Avrigeanu and Marilena Avrigeanu

Horia Hulubei National Institute for Physics & Nuclear Engineering (IFIN-HH), Bucharest-Magurele, Romania

Content

Why 1. Introduction: motivation for our actual largest interest in NLD (σ) & RSF

How 2. Spin cutoff for / from isomeric cross-section model calculations

why (see A.C. Larsen+, PRC **83**, 034315 (2011), Sec. **III.E**)

What 3. An E1 RSF EGLO model

Conclusions (?)

Motivation: Nuclear Data (ND) *consistent* model calculations @ IFIN-HH

[E.D. Arthur – P.G. Young, LANL, '80]

YES

[IAEA/NDS RCs/RA (15), IFIN-HH, 1982-2009]

i. unitary use of *common model parameters* for different mechanisms

ii. use of *consistent sets* of input parameters (OMP, NLD, RSF, …) - determined by *analyses of various independent* experimental data

iii. unitary account of *whole body* of related experimental data for *isotope chains* and *neighboring elements*

[activation & particle-emission spectra]

[enlarged incident-energy range]

NO re-normalization or free parameters (widely-used within ND libraries)

Motivation - ND calculations @ IFIN-HH: methods, tools, input parameters

- **Pure elastic scattering OP analysis**
  SCAT2 [O. Bersillon]
  - phenomenological OP
    + semi-microscopic (DF) OP (local version)

*Phys. Rev. C**62** (2000) 017001*
*Nucl. Phys. **A693** (2001) 616*
*Eur. Phys. J. **A12** (2001) 399*
Int. J. of Mod. Phys. E, 11 (2002) 249
*Nucl. Phys. **A**723 (2003) 104*
*Nucl. Phys. **A** 759 (2005) 327*
*Nucl. Phys. **A** 764 (2006) 246*

- **Coupled Reaction Channel (CRC)**
  FRESCO-2003 [I.J. Thompson]

- **Composite system equilibration**
  - **Geometry Dependent Hybrid** (GDH) preequilibrium-emission model
  - **Hauser-Feshbach** (HF) statistical model

  - **STAPRE-H95** [V. Avrigeanu, M. Avrigeanu] (updated - 2013)

  - **TALYS-1.4** [A. Koning, S. Hilaire, M. Duijvestijn]

Motivation - ND calculations @ IFIN-HH: methods, tools, input parameters

LOCAL APPROACH:

STAPRE-H95 (updated-2013..) [OM/PE/SM: SCAT2, GDH, HF]

- **neutron-spherical OMP** [Koning-Delaroche, Nucl.Phys. **A713**, 231 (2003)]
- **p-, α- spherical OMP:** [KD (2003), V. Avrigeanu+, PRC **49**, 2125 (1994) - NOT: M. Avrigeanu+, PRC **82**, 014606 (2010)]
- **γ-ray strength functions:**
  - **1985 - 2012: E1: EDBW (LLNL-1982, IFIN-1987) , M1 (SLO, 1990)**
  - **2012 – on: E1: GLO (1990), EGLO+ (2010, 2012)**
- **PE: Geometry Dependent Hybrid model** [M. Blann+, PRC **28**, 1493 (1984)]
  - **+ α-particle emission** [Z.Phys. A **329**,177(1988)]
  - **+ J^{π}-conservation** [Z.Phys. A **329**,177(1988)]
  - **+ $g_{FGM}(e)$, $A_K(p,h)$, $f_K(p,h,E,F_1(l,E_i)$** [Phys. Rev. C **58**, 295 (1998)]
- **Nuclear-level density: BSFG:**
  - **+ $E^*<B_n$: (a,Δ) from fit of [D_0 (RIPL1,-3), N_d (ENSDF,RIPL3)]**
  - **+ $E^*>B_n$: $a(E^*)$** [A.R. Junghans+, NP**A629**, 635 (1998); A.J. Koning, M.B. Chadwick, PRC **56**, 970 (1997)]
  - **+ I/I_r: 0.5(g.s.)-0.75(B_n)-1(15 MeV)** [V.Avrigeanu+, JNST **S2**,746 (2002), .. **?** - V.Avrigeanu+, PRC **85**, 044618 (2012)]

Motivation - (α,α), (α,x) analysis @ A=121-209 [2010 – on]

PHYSICAL REVIEW C **82**, 014606 (2010)

α-particle nuclear surface absorption below the Coulomb barrier in heavy nuclei

M. Avrigeanu and V. Avrigeanu*

"Horia Hulubei" National Institute for Physics and Nuclear Engineering, Post Office Box MG-6, R-077125 Bucharest-Magurele, Romania

(Received 7 April 2010; revised manuscript received 3 May 2010; published 7 July 2010)

An analysis of all available α-particle-induced reaction cross sections on nuclei within the mass number range $121 \leqslant A \leqslant 197$, below the Coulomb barrier, is carried out. This analysis leads to an optical potential that describes the α-particle elastic scattering at low energies as well and both elastic-scattering and reaction data for $45 \leqslant A \leqslant 124$. The energy dependence of the surface imaginary potential depth is proved to be essential for understanding α-particle interaction behavior below th

DOI: 10.1103/PhysRevC.82.014606 P

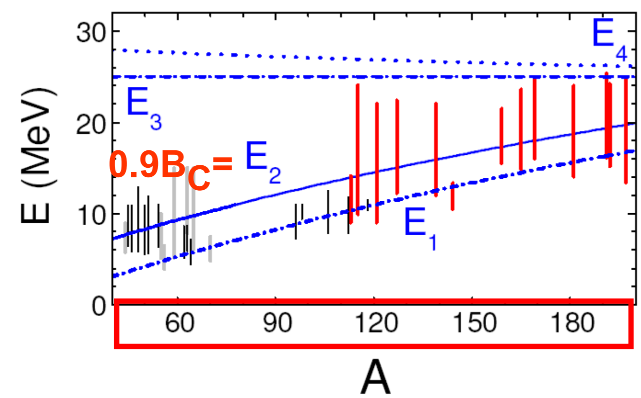


FIG. 1: (Color online) The A-dependence of energies E_1 (dash-dotted) below which the depth W_D is constant, E_2 (solid) corresponding to $0.9B$, E_3 (dashed) and E_4 (dotted) given in Table I, and the energy ranges (thick bars) of the (α, x) reaction data involved in this work for A>113 as well as formerly analyzed (thin bars) and additionally checked in Ref. [2] for A <90.

Motivation - (α,α), (α,x) analysis @ A=121-209 [2010 – on]

PHYSICAL REVIEW C **82**, 014606 (2010)

α-particle nuclear surface absorption below the Coulomb barrier in heavy nuclei

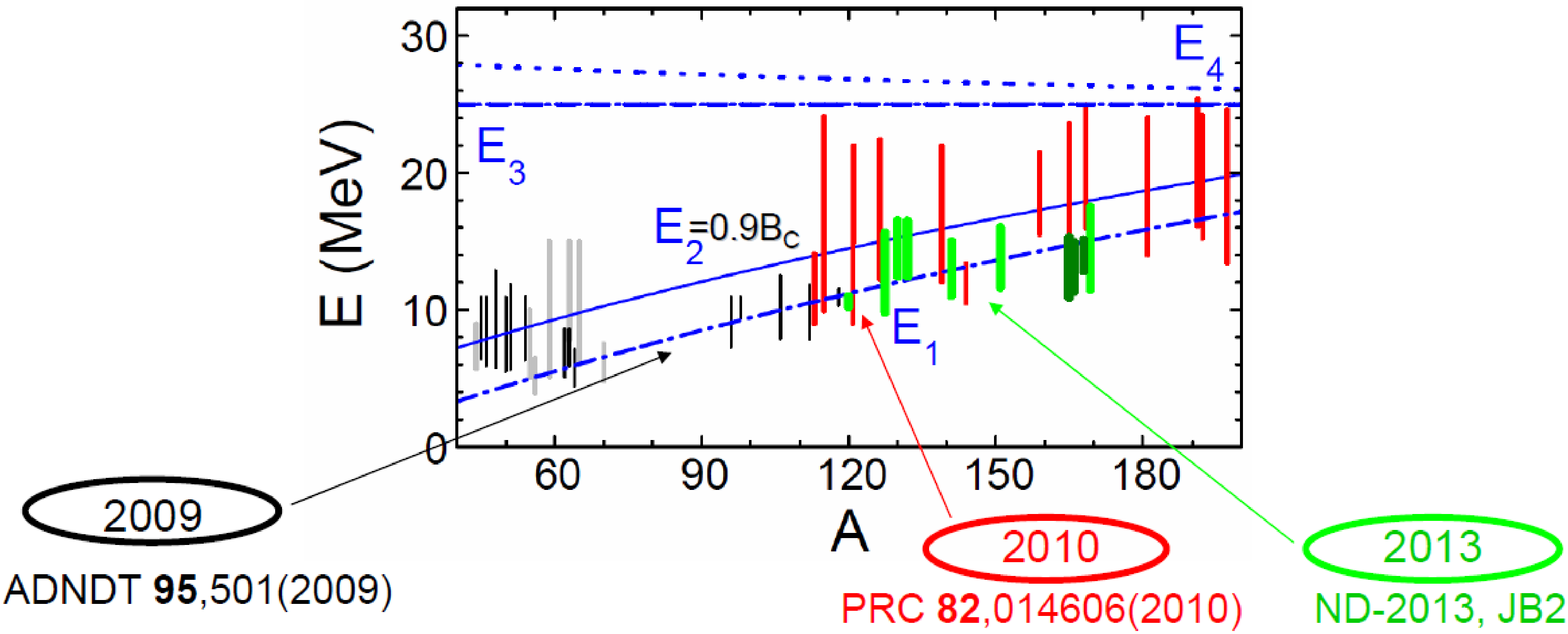


FIG. 1: (Color online) The A-dependence of energies E_1 (dash-dotted) below which the depth W_D is constant, E_2 (solid) corresponding to $0.9B$, E_3 (dashed) and E_4 (dotted) given in Table I, and the energy ranges (thick bars) of the (α, x) reaction data involved in this work for $A{>}113$ as well

Motivation - (α,α), (α,x) analysis @ A=121-209 [2010 – on]

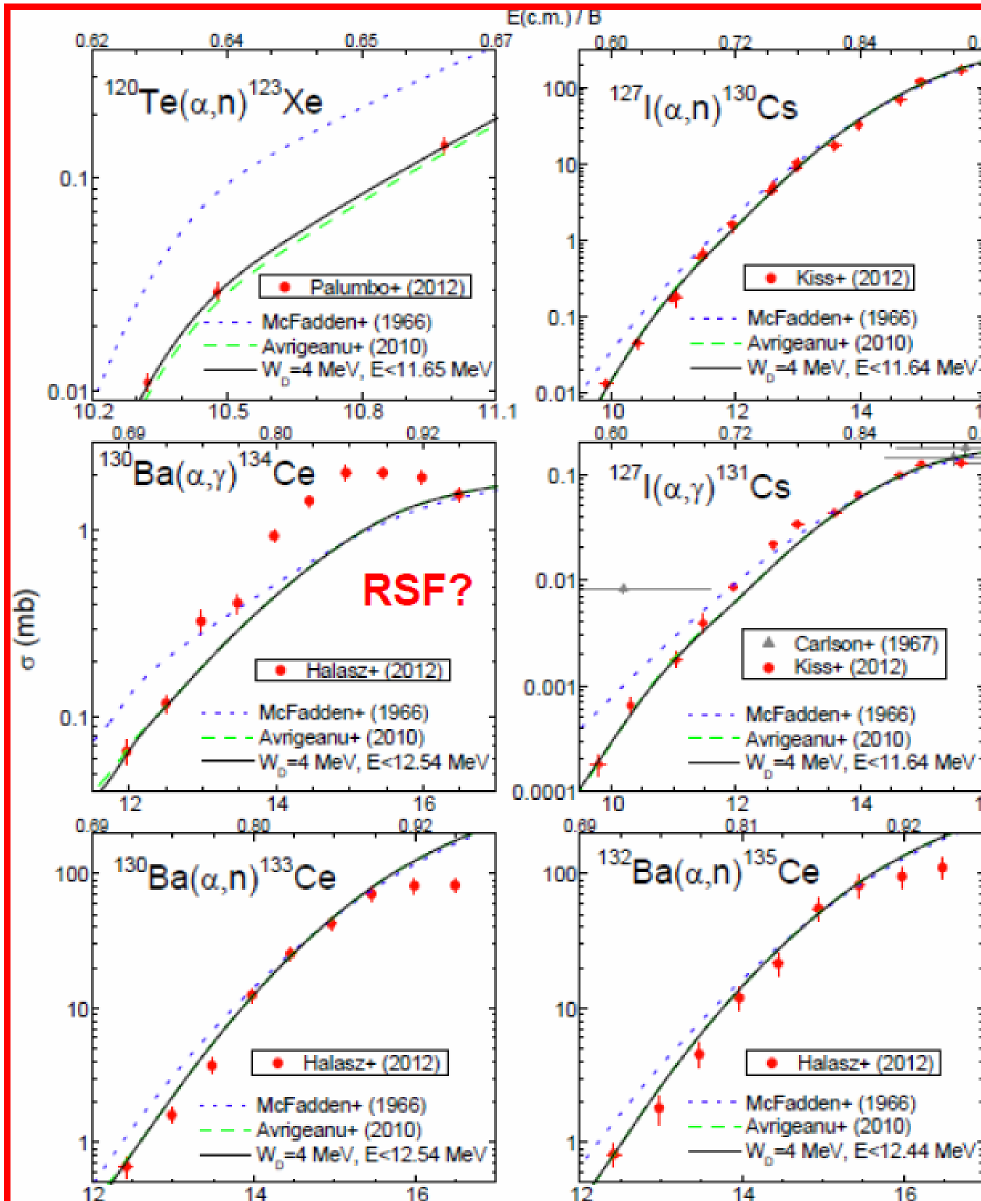


Fig.5 [ND-2013 – JB2]

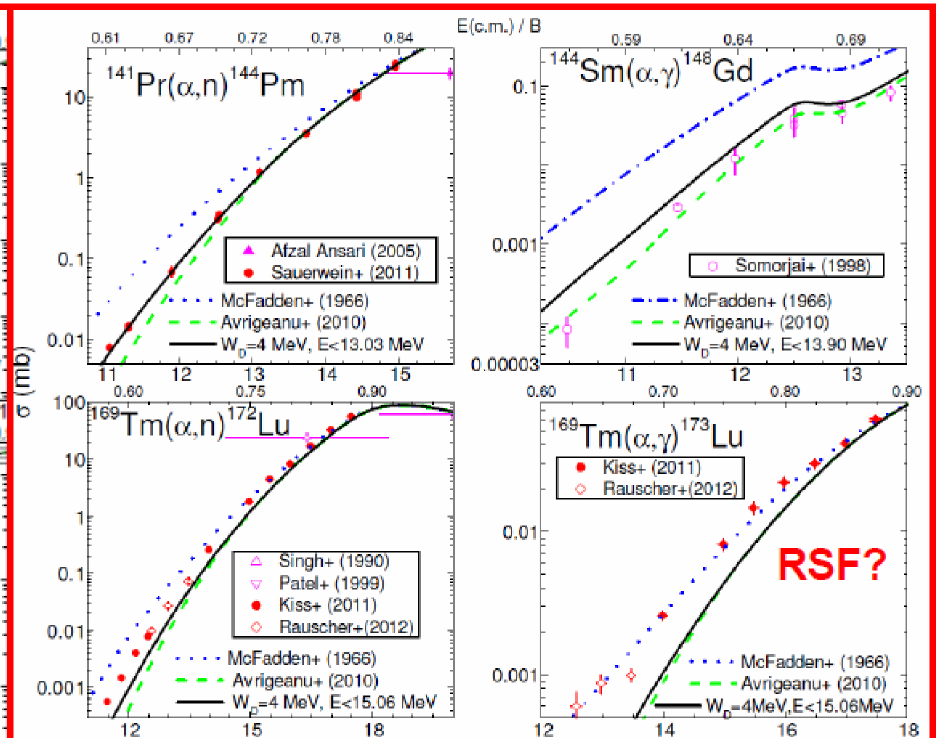
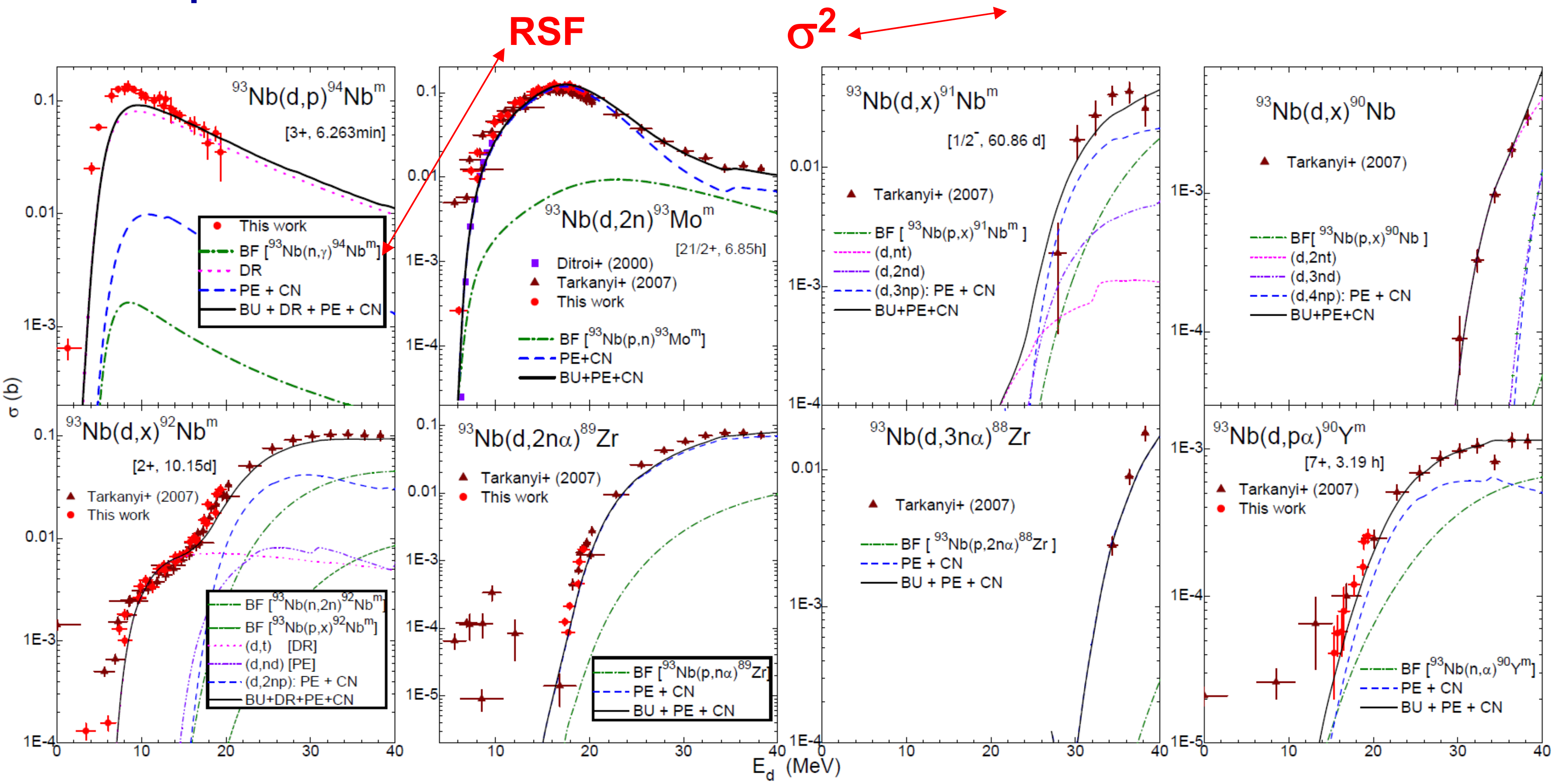


Fig.6 [ND-2013 – JB2]

preliminary results

Motivation - isomeric cross-section model calculations for F4E / ITER [2009 – on]

Most experimental data - used for model validation – are for isomeric states:



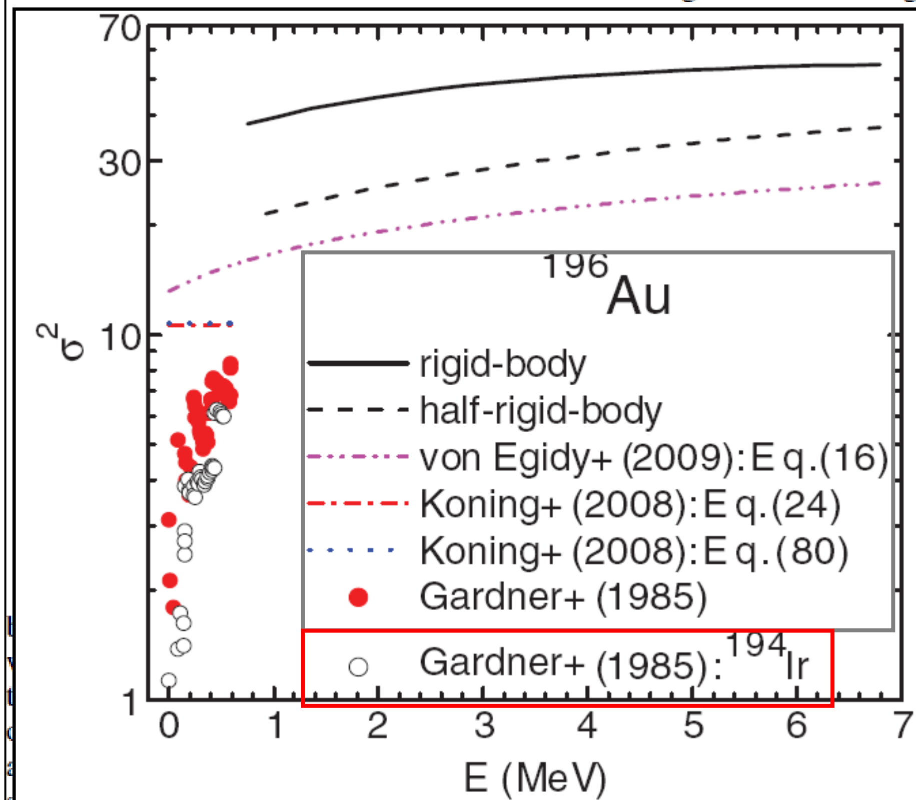
[E.Semeckova+, PRC **85**, 034603 (2012),
M.Avrigeanu+, PRC **84**, 014605 (2011),
M.Avrigeanu+, PRC **82**, 037601 (2010),
P.Bem+, PRC **79**, 044610 (2009),
M.Avrigeanu+, Fus.Eng.Des. **84**, 418 (2009)]

2. Spin cutoff for / from isomeric cross-section model calculations

PHYSICAL REVIEW C **85**, 044618 (2012)

Isomeric cross sections of fast-neutron-induced reactions on ^{197}Au

M. Avrigeanu and V. Avrigeanu*



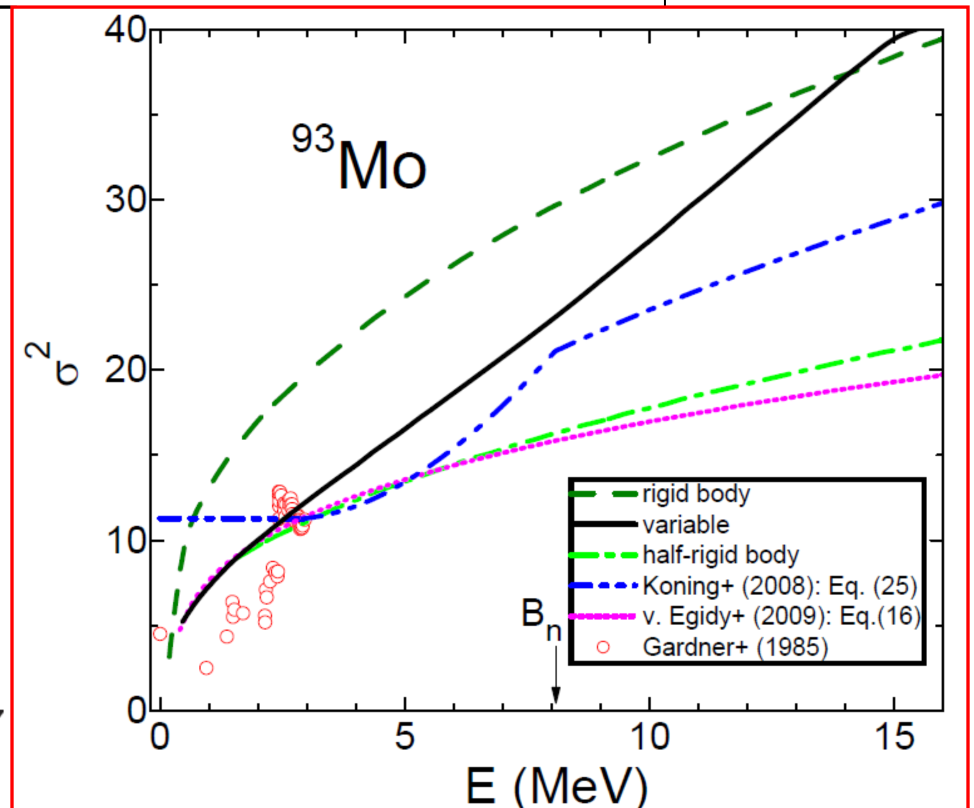


FIG. 5. (Color online) The excitation-energy dependence of the level density spin cutoff for the nucleus ^{196}Au corresponding to rigid-body (solid curve) and half rigid-body (dashed) moments of inertia, the energy-dependent parametrization of Ref. [45] (dash-dot-dotted), the discrete spin cutoff (dash-dotted) and its global value (dotted) of Ref. [47], and given by the maximum likelihood estimator [90] (solid circles). The latest quantity is also shown for the nucleus ^{194}Ir (open circles).

of inertia which is defined by the energies of the lowest
level at a given spin J of the nucleus (the yrast levels
as thus emphasized that, while the former is related to
f noninteracting particles, the latter is consistent with
site shell model calculations corresponding roughly
0.5. The shell structure may also account for values
or nuclei away from closed shells, and for the opposed
nuclei near closed shells [7].
mainly constant σ^2 values were related formerly to a
temperature (CT) level density formula. Hilmann and

I. Nuclear Level-Density (NLD)

- Bethe (1937): σ^2 implicit: Fermi-Gas (FG) NLD formula
- Bloch (1954): $\sigma^2 \leftrightarrow$ rigid-body rotations of whole nucleus
- Ericson (1959): $\sigma^2 = I^*t/\hbar^2$, M.o.I.: $I = I_r$ (t-high limit), $I = 0.7I_r$ (+pairing)
- Huizenga-Vandenbosch (1960): $\sigma_m/\sigma_g = f(\sigma^2)$
- Grover (1961): statistical model (NLD) + γ-decay, $I/I_r = 0.1$-1.6
- Grover (1962): FG NLD I/I_r vs. $(J_{yr},E_{yr}) \rightarrow I_{eff}/I_r \sim 0.5$ cf. Shell Model (SM)
- Grover (1967): SM: $I<I_r$ (away from closed shells), $I>I_r$ (closed shells)
- Hilmann-Grover (1969): SM + BCS-pairing: $I=f(E^*,J)$
- Gilat (1970): SM analytical approx.: $I_r \leftrightarrow \sigma^2(A)$ average trend
- Lu+ (1972): (α,x) DA analysis: $I/I_r \sim 1$; **$I/I_r<1$ $\leftrightarrow$ incorrec**
- Hille+ (1974): DA analysis: $I/I_r \sim 1$; **$I/I_r \sim 0.5$ $\leftrightarrow$ incorrect**
- Canty+ (1979): SM$\rightarrow$FG params.: shell-effects washin
- Joly+ (1979): (n,γ) analysis: ^{104}Rh, ^{198}Au: $I/I_r=1$, ^{170}Tm:
- Weigmann+ (1981): ^{41}K - **D_{0p}/D_{0n} analysis**: $I/I_r = 1.00 \pm ($
- Avrigeanu+ (2002): ^{51}V - **D_{0p}/D_{0n} analysis**: $I/I_r = 0.75 \pm ($

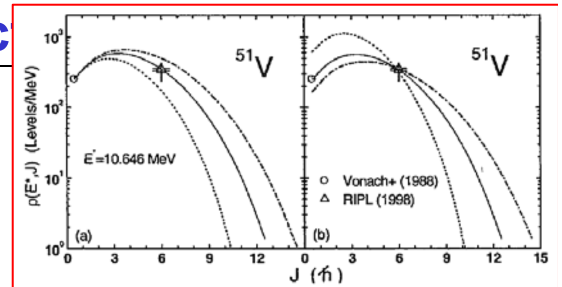


Fig. 1 Comparison of the spin–dependent level densities of the nucleus ^{51}V at the excitation energy of 10.646 MeV corresponding to the experimental D_0^p by Vonach *et al.*[4] and D_0^n given in RIPL[6] extrapolated at this energy, and the BSFG values. The calculated values correspond to the I/I_r–ratio values 0.5 (dotted curves), 0.75 (solid curves), and 1 (dash–dotted curves), and the fit of the low–lying discrete levels as well as (a) the D_0^p value,[4] and (b) the D_0^n values.[6]

σ^2 <-- Moment-of-Inertia in nuclear reaction/structure

- Ignatyuk+ (1993): Generalized Superfluid Model: phase transition: $T_C \sim 12/A^{1/2}$
- Mughabghab-Dunford (1988): NLD-systematics: I/I_r=0.5 - surprising cf. GSM!
- Agrawal+ (1999): pairing correlations: I/I_r~0.5 at low E*; +15% at higher E*
- Dean+ (1995), Langanke+ (1997): SMMC: I/I_r=0.5 – 1 ↔ T=0 – 1-1.5 MeV
- Alhassid+ (2005): simplified spin-cutoff model: - idem -
- Alhassid+ (2007): SMMC: I(E*): $I<I_r$ (low E*) [pairing correlations]

II. Spectroscopic data

- Sorensen (1973): I/I_r(J): 0.3-0.5 (low J, pairing correlations) – 1 (J~14 $\hbar^2$, BB)
- Bohr-Mottelson(1981): *dynamical* I_{eff} ↔ yrast bands envelope (superfluid ph.)
- Martin-v.Egidy (1995): MoI large-change↔transitional nuclei (shape,pairing)
- Delaplanque+ (2004): shell effect: $I<I_r$ at J-high/normal ph., as superfluid ph.
- Gupta-Hamilton (2011): MoI fast-increase with J ↔ shape transitional nuclei
- v.Egidy+ (1986,1988,2009): σ^2=f(A) – weak ↔ $I<I_r$, E*<6-8 MeV; σ^2=f(A,E*)
- Chadwick-Young(1991): σ^2_d + interpolation→σ^2_{FG}(E*=B)
- Al-Quraishi+ (2003): 20<A<110: $I \leq I_r$, E*<few MeV
- Koning+(2008): $E^*_d=(E_U-E_L)/2$: σ^2_d [$\sigma^2_{d,global}=(0.83A^{0.26})^2$]; interpolation→$\sigma^2$(B)

III. E*-, A-dependent M.o.I.

- Avrigeanu+ (2002): **$I/I_r(E^*)$**: 0.5 (g.s.) – 0.75(B_n) – 1.0 ($E^*\approx$15MeV) [^{51}V]
- Semkova+ (2004), Reimer+ (2004), Avrigeanu+(2006,..): [$\rightarrow\sigma_m/\sigma_g$,A=58-184]
- Hilgers+(2007), Sudar+ (2006,2010,2011): I/I_r=0.15-0.3, A=140-200$\rightarrow$ **$I/I_r(A)$**
- Semkova+ (2009): I/I_r~0.5, A~208

IV. PE vs. CN spin distribution

- Feshbach-Kerman-Koonin (1980): PE ($n\sim\tilde{n}$): $\sigma^2_F(n)\approx 0.16nA^{2/3}$
- Reffo-Hermann (1982): PE (n=2): $\sigma^2(n)\approx 0.28nA^{2/3}$
- Fu (1986): PE: $\sigma^2(E,n)$
- Bogila+ (1995): $\sigma^2(E,n)\rightarrow\sigma_m/\sigma_g$
- Chadwick+ (1994): σ_m/σ_g (^{178}Hf^{m2}, 16$^+$) description $\leftrightarrow$ **$\sigma^2(E,n)\neq\sigma^2_{HF}$**
- Kawano+ (2006): **$\sigma^2(E,n)=\sigma^2_{HF}$**$\rightarrow\sigma_m$(^{193}Ir^m,11/2$^-$) reduction: **-50%** (E=14MeV)
- Dashdorf+(2007): $\boxed{\boldsymbol{\sigma^2(E,n)=\sigma^2_{HF}\longleftrightarrow I/I_r<1} \text{ [Hilgers+ (2007), Sudar+ (2006)]}}$
- Fotiades+ (2009): **$\sigma^2(E,n)\neq\sigma^2_{HF}\longrightarrow I/I_r\approx 1$**

3. An E1 RSF EGLO model

Larsen-Goriely,
PRC **82**, 014318 (2010):
GLO [PRC **41**, 1941 (1990)] +

$$\Gamma(E_\gamma, T_f) = \frac{\Gamma_{E1}}{E_{E1}^2}\left[E_\gamma^2 + \frac{4\pi^2 T_f^2 \boxed{E_{E1}}}{\boxed{(E_\gamma + \delta)}}\right], \quad T$$

Daoutidis-Goriely,
PRC **86**, 034328 (2012): T_f=0.5 Me

Present work:

$T_f = (U_t/a)^{1/2}$

$U=U_t+U_r$, $U_r \sim J(J+1)\hbar/(2\mathcal{I}$

[D.W. Lang, NP **77**,545(1966)
P. Cejnar, PRC **52**, 919(1995)]

PHYSICAL REVIEW C VOLUME 38, NUMBER 2 AUGUST 1988

Statistical $E1$ and $M1$ gamma strength functions from heavy-ion, $xn\gamma$ data

G. A. Leander
UNISOR, Oak Ridge Associated Universities, Oak Ridge, Tennessee 37830
(Received 6 July 1987)

A statistical model analysis of heavy-ion, $xn\gamma$ data puts constraints on the electromagnetic dipole strength functions at low energies, $E_\gamma \sim 0.5-4$ MeV. The $M1$ strength is inferred to be up to an order of magnitude smaller than at the higher energies of neutron capture gamma rays. The analysis supports the Kadmensky-Mark
tail of the giant resonance that
considered include the yrast fe
^{152}Dy up to spin 60$\hbar$.

I. INTRODUCTION

Considering the complexity of the nucle
natural from the outset of nuclear physic
scribe nuclear reactions as statistical proc
by the available phase space.[1] This is usef
bility for going into different parts of phas
given by simple and general prescriptions.
concerned with such global probabilities
functions" for electromagnetic dipole tran
tempts to express them as simple functio
number A, the energies of the initial and f
the collective deformation of the nuclea
functions have been the topic of much res
three decades. Empirical information has
study of

(i) photonuclear absorption, which has
cross section for electromagnetic transiti
the region above 10 MeV, around the pea
$E1$ resonance;[2]

(ii) capture gamma rays, in particular
MeV gamma radiation following neutron c

(iii) electromagnetic transitions betwee
els,[4] mostly with $E_\gamma \lesssim 1$ MeV.

The evaporation residues of heavy-ion f
are formed at high spins, and each one emi
ber of gamma rays in the range $E_\gamma \sim 0.5$-

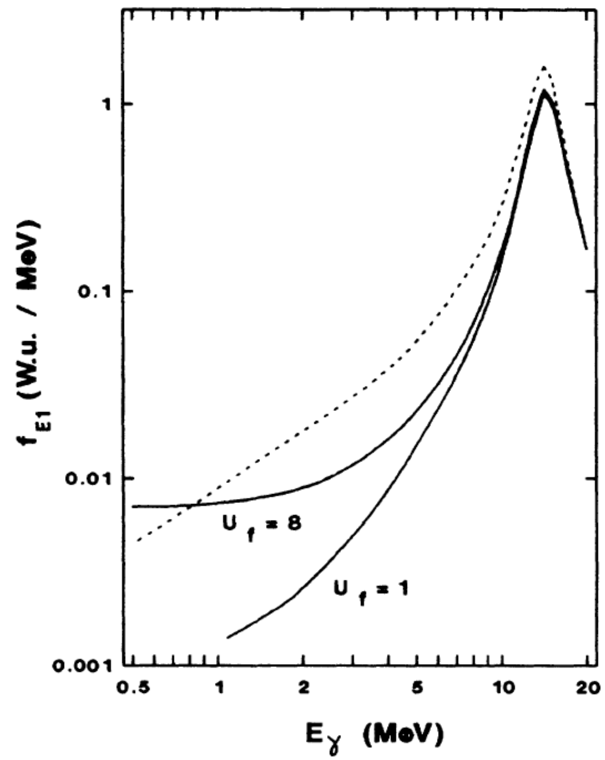


FIG. 2. $E1$ strength functions. The dashed curve is the line shape based on a Lorentzian cross section, with the standard parameters from Table I for spherical shape and $A=160$. The solid curves show the Kadmensky-Markushev-Furman line shape, for a high ($U_f = 8$) and a low ($U_f = 1$) value of the intrinsic energy in the final state.

3. An E1 RSF EGLO model

Larsen-Goriely,
PRC **82**, 014318 (2010):
GLO [PRC **41**, 1941 (1990)] +

$$\Gamma(E_\gamma, T_f) = \frac{\Gamma_{E1}}{E_{E1}^2}\left[E_\gamma^2 + \frac{4\pi^2 T_f^2 \boxed{E_{E1}}}{\boxed{(E_\gamma + \delta)}}\right]$$

T_f=0.15 MeV

Daoutidis-Goriely,
PRC **86**,034328(2012): T_f=0.5 MeV

PHYSICAL REVIEW C VOLUME 38, NUMBER 2 AUGUST 1988

Statistical

A statistical
strength funct
der of magnit
supports the
tail of the gia
considered in
^{152}Dy up to sp

I. INTRO

Considering the complex
natural from the outset of
scribe nuclear reactions as
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tempts to express them as
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the collective deformation
functions have been the to
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study of
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cross section for electrom
the region above 10 MeV,
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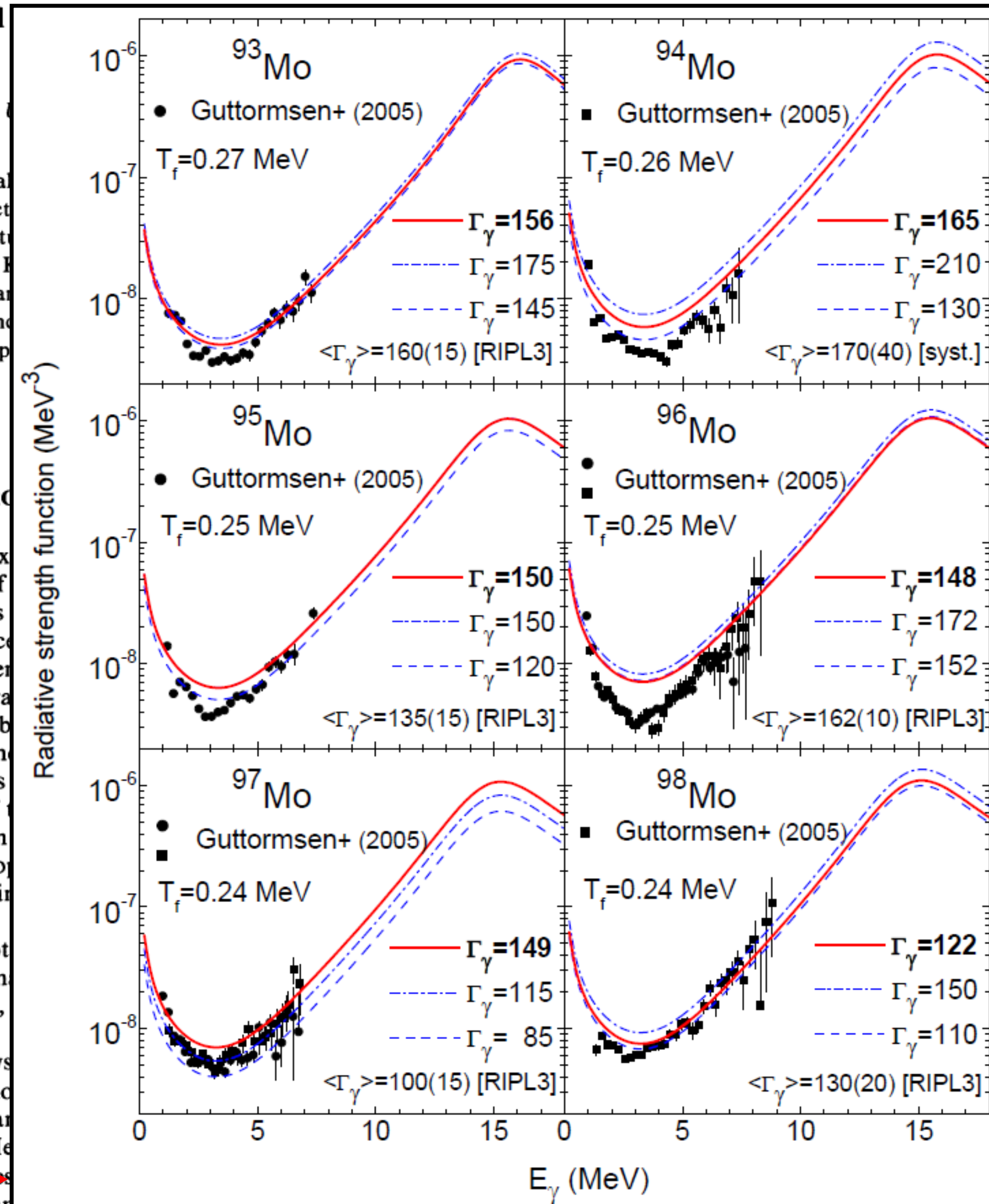
(ii) capture gamma rays
MeV gamma radiation follo
(iii) electromagnetic tra
els,[4] mostly with $E_\gamma \lesssim 1$ Me
~~The evaporation residu~~
are formed at high spins, a
ber of gamma rays in the range $E_\gamma \sim 0.5$- sic energy in the final state.



Present work:

$T_f = (U_t/a)^{½}$

$U=U_t+U_r$, $U_r \sim J(J+1)\hbar/(2I)$

[D.W. Lang, NP **77**,545(1966)
P. Cejnar, PRC **52**, 919(1995)]

U_t~1 MeV

[G.A. Leander, PRC **38**,728(1988)]

U_t=0.7 MeV

3. An E1 RSF EGLO model

Larsen-Goriely,
PRC **82**, 014318 (2010):
GLO [PRC **41**, 1941 (1990)] +

$$\Gamma(E_\gamma, T_f) = \frac{\Gamma_{E1}}{E_{E1}^2}\left[E_\gamma^2 + \frac{4\pi^2 T_f^2 \boxed{E_{E1}}}{\boxed{(E_\gamma + \delta)}}\right]$$

T_f=0.15 MeV

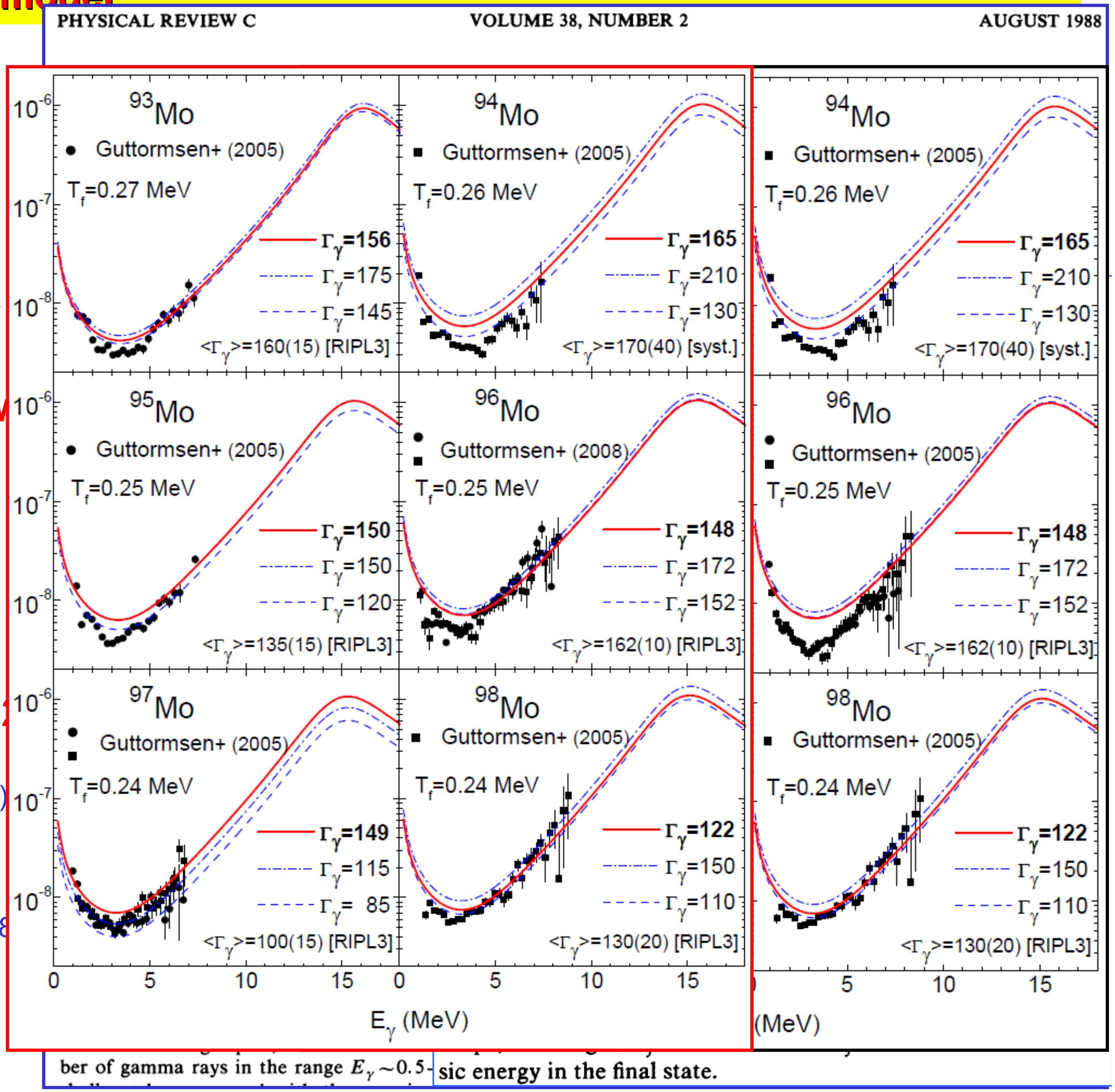
Daoutidis-Goriely,
PRC **86**,034328(2012): **T_f=0.5 M**

Present work:
$T_f = (U_t/a)^{½}$
$U=U_t+U_r$, U_r~$J(J+1)\hbar/($
[D.W. Lang, NP **77**,545(1966)
P. Cejnar, PRC **52**, 919(1995)

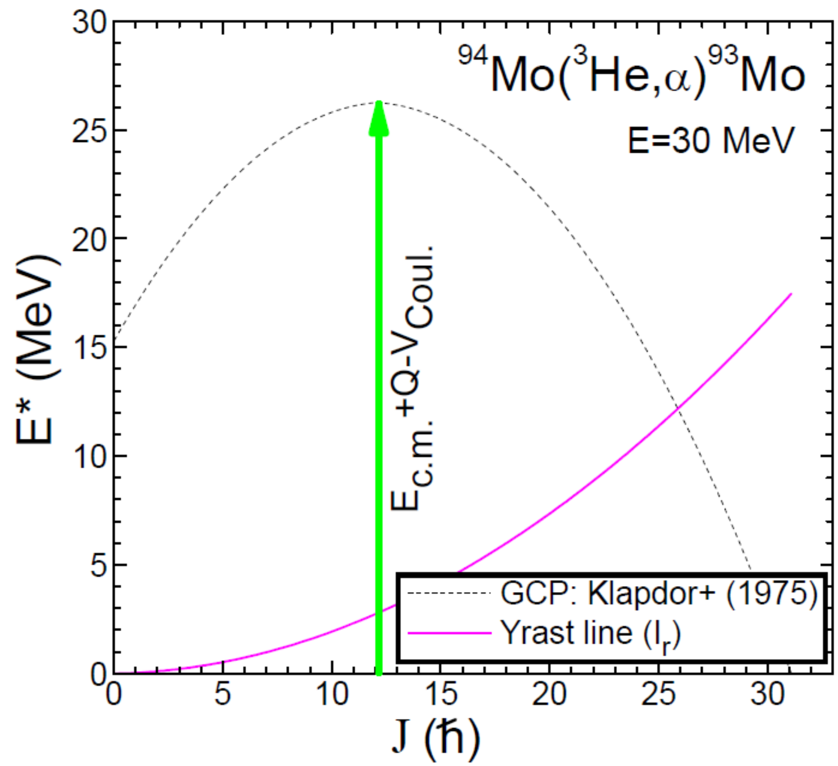
U_t~1 MeV

[G.A. Leander, PRC **38**,728(198

U_t=0.7 MeV



Residual nuclei population (TALYS-1.4)



TALYS-1.4 results:

- Total reaction cross section: 1292 mb
  - DR: 30 mb
  - PE: 1262 mb
- (^{3}He,α): α-particle: - av. energy = 33.7 MeV
  - peak energy = 37 MeV → **U_t~0.7 MeV**
- ^{93}Mo population: E*=2.3-18.7 MeV (FWHM)
  J= 4.5-9.5 hbar (FWHM)

Calculated cross-section sensitivity vs. $f_{E1}(E\gamma)$

S. Harissopulos et al. / Nuclear Physics A 758 (2005) 505c–508c

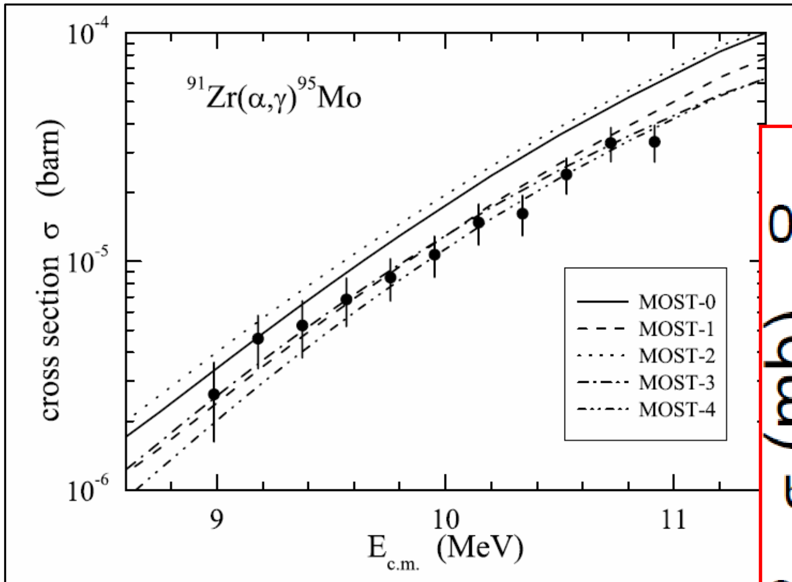
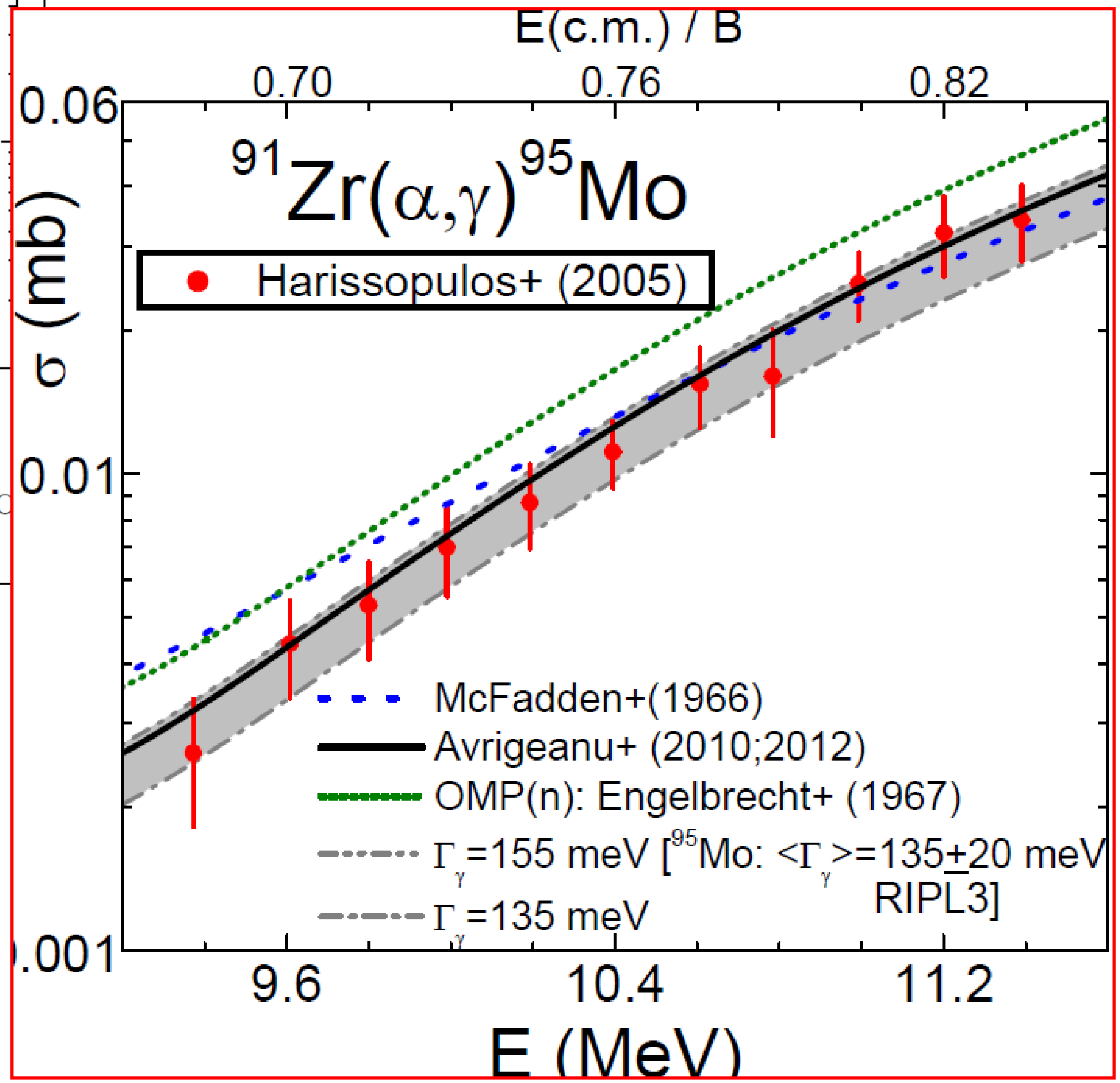


Figure 5. Cross sections measured fo
the ^{91}Zr$(\alpha,\gamma)^{95}$Mo reaction.



Conclusions

Thank you for your attention !

- **Results**
  - ❑ σ^2 with variable moment of inertia: (0.5-0.75-1.)*I_r [E*=0- B - 15 MeV]
  - ❑ need of accurate <u>p-resonance</u> data for nuclei n-resonance data
  - ❑ use of U_t=0.7 MeV for $f_{E1}(E\gamma)$ low-energy enhancement of Mo isotopes

- **Open Questions**
  - ➢ $f_{E1}(E\gamma)$ low-energy enhancement of ^{111,112}Cd and Sn isotopes