F4E-GRT-168.02, Tasks 8.1

5th Workshop on Nuclear Level Density & Gamma Strength, Oslo, May 18-22, 2015
[http://tid.uio.no/workshop2015/]

Realistic radiative strength functions (RSFs) within α-particle induced reactions and emission in the mass range A~70

Vlad Avrigeanu and Marilena Avrigeanu

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Content

1. **Motivation: - recent (α,γ), newest (p,γ) / (p,α) reaction c.s. - VAGUE account** (framework)
   - NEED of consistent input model parameters for study of α-OMP
2. **E1 RSF EGLO model and parameters for A~70**
3. **RSF effects on calculated (α,γ) on ^{64}Zn, (p,γ), (p,α) on ^{64,66,68,70}Zn reaction c.s.**
4. **Conclusion**

1. Motivation: newest (p,γ) / (p,α) reaction c.s. – vague account (1/4)

PHYSICAL REVIEW C **90**, 052801(R) (2014)

Direct study of the α-nucleus optical potential at astrophysical energies using the $^{64}Zn(p,\alpha)^{61}Cu$ reaction

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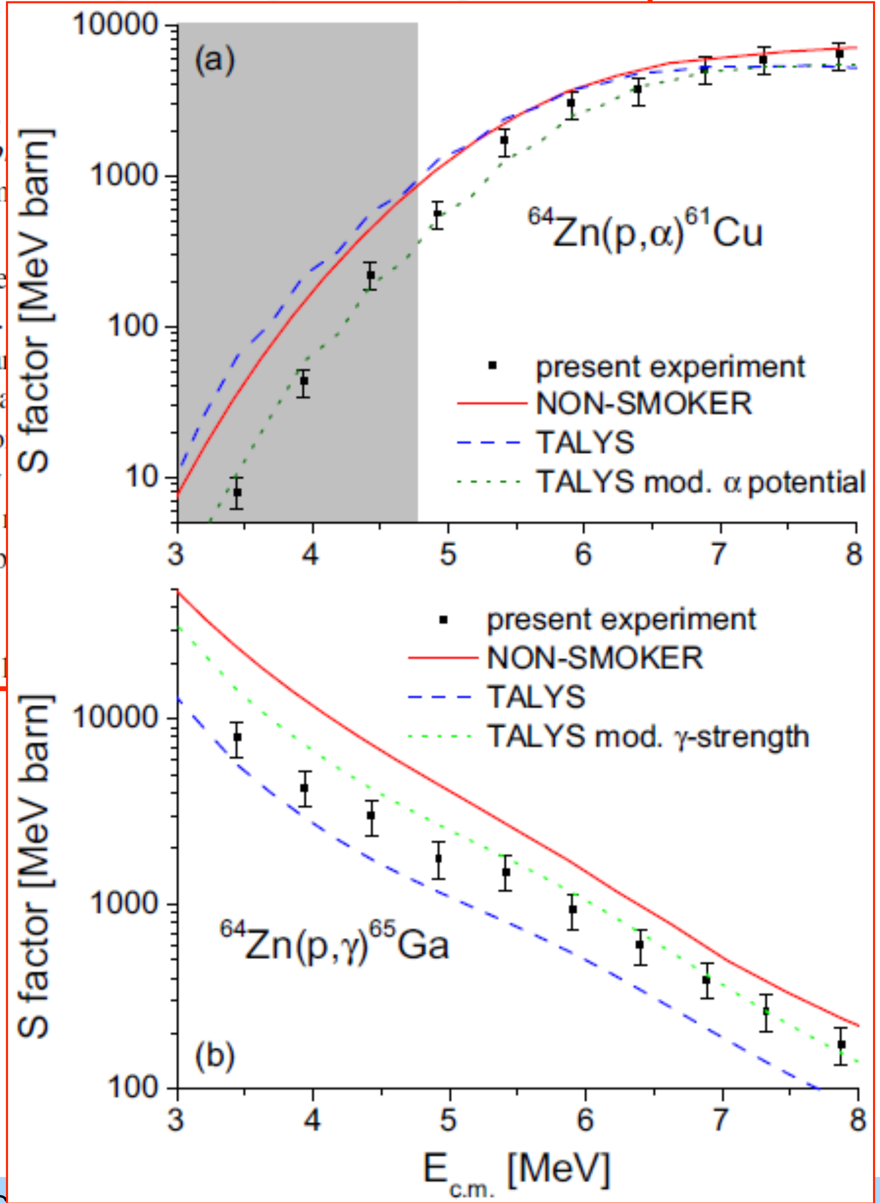
Institute for Nuclear Research (Atomki), H-4001 Deb
(Received 1 October 2014; published 26 Novem

In the model calculations of heavy element nucleosynthesis processes the statistical model calculations which utilize various nuclear input parameters. involving α particles the calculations bear a high uncertainty owing to the la optical potential. Experiments are typically restricted to higher energies consequences can be drawn. In the present work a (*p*,α) reaction is used fo optical potential. The measured $^{64}Zn(p,\alpha)^{61}Cu$ cross section is uniquely and the measurement covers the whole astrophysically relevant energy calculations, direct evidence is provided for the incorrectness of global op models.

DOI: 10.1103/PhysRevC.90.052801 PACS number(s): 24.



Framework: Nuclear Data (ND) *consistent* model analysis @ 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)

Framework - ND analysis @ IFIN-HH: methods, tools, input parameters (3/4)

- **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 - 2014)
  - **TALYS-1.6** [A. Koning, S. Hilaire, M. Duijvestijn]

LOCAL APPRO

STAPRE-H95 (

– n-, p- spheric

– α- spherical

– γ-ray strengt

• E1: GLO

• M1: SLO

– PE: Geometr

+ α-pa

+ J^{π}-co

+ g_{FGM}

– Nuclear-leve

+ E*<E

+ E*>E

+ I/I_r: 0.5(g.s.)-0.75(B_n)-1(15 MeV)

[M. Avrigeanu+, PRC **88**,014612

Journal of NUCLEAR SCIENCE and TECHNOLOGY, Supplement 2, p. 746–749 (August 2002)

On Consistent Description of Nuclear Level Density

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The back–shifted Fermi gas (BSFG) model has been used for description of the nuclear level density at excitation energies up to the nucleon binding energy by fitting the latest experimental low–lying discrete levels and average s–wave nucleon resonance spacings D_0. The analysis of the ratio of the proton and neutron resonance spacings corresponding to the same compound nucleus has led to the ratio I/I_r=(0.75±0.06) of the effective moment of inertia of the nucleus

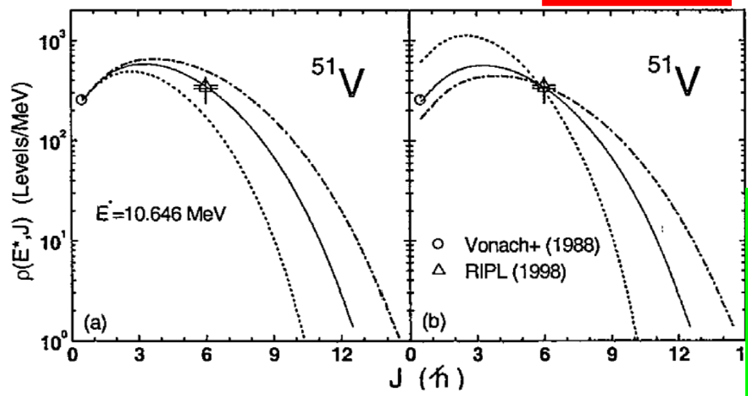
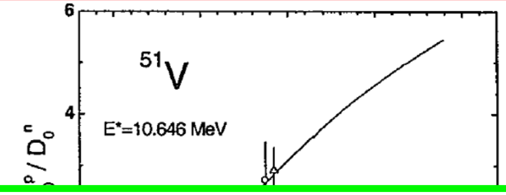


Fig. 1 Comparison of the spin–dependent level densities of the nucleus ^{51}V at the excitation energy of 10.646 MeV corresponding to the experimental D_0^p by Vonach *et al.*[4] and D_0^n given in RIPL[6] extrapolated at this energy, and the BSFG value. The calculated values correspond to the I/I_r–ratio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



LOW-ENERGY DEUTERON-INDUCED REACTIONS ON ^{93}Nb

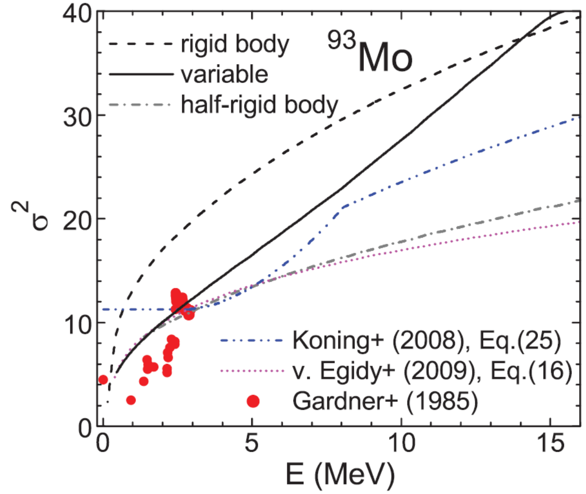


FIG. 5. (Color online) The excitation-energy dependence of the level density spin cutoff for the nucleus ^{93}Mo, corresponding to the rigid-body (dashed curve), half-rigid-body (dash-dotted), and variable [61] (solid curve) moment of inertia, the discrete value for the

2. E1 RSF EGLO model and parameters for A~70 (1/4)

Larsen-Goriely, PRC **82**, 014318 (2010):

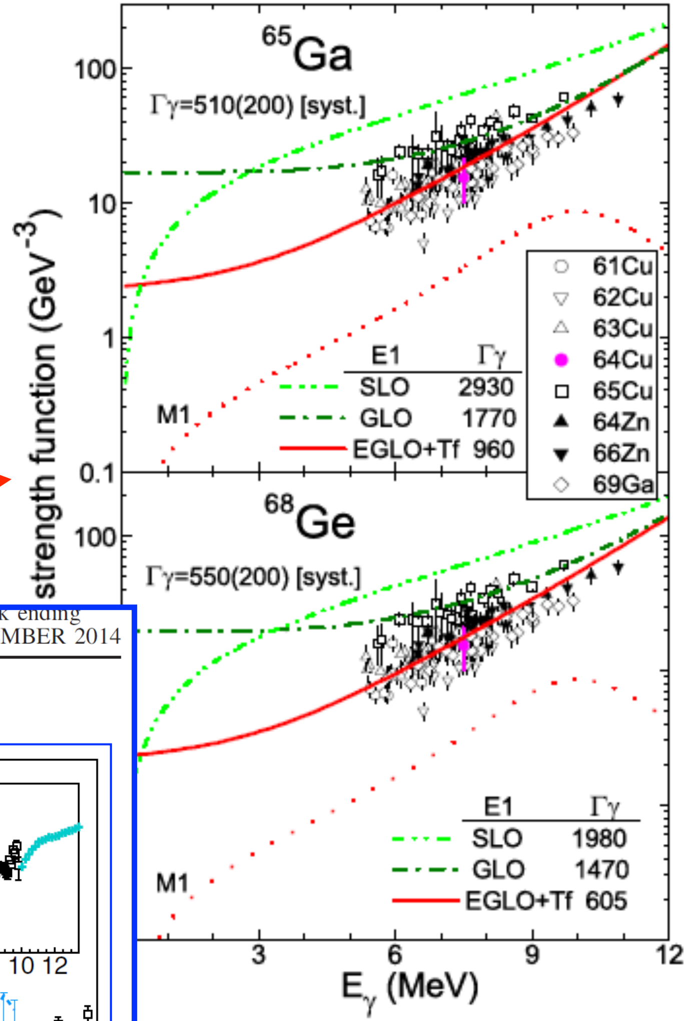
GLO [PRC **41**, 1941 (1990)] +

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

T_f=0.15 MeV

Daoutidis-Goriely, PRC **86**, 034328 (2012):

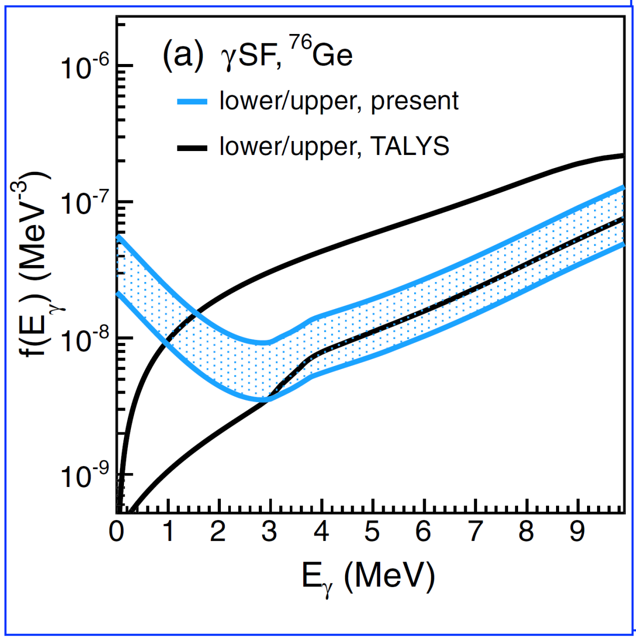
T_f=0.5 MeV

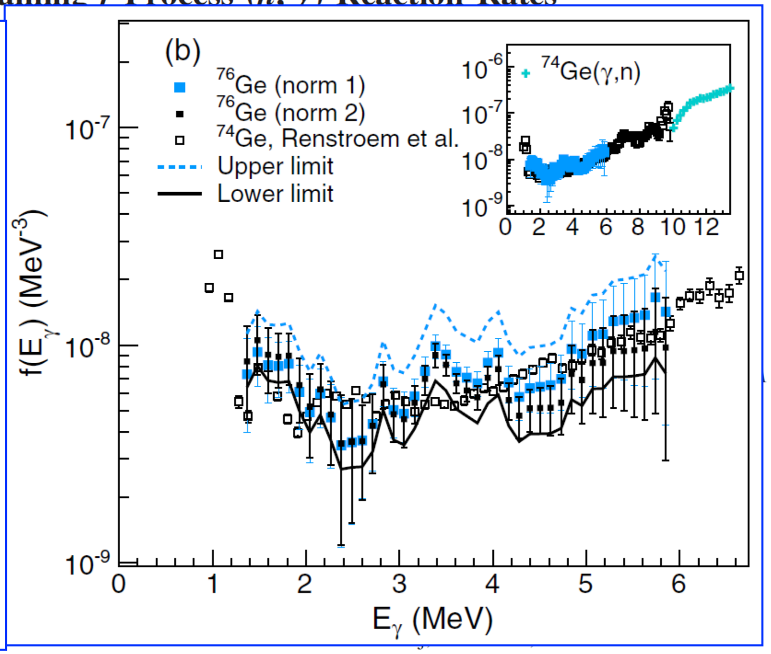


online) Comparison of calculated γ-ray of the $E1$ and $M1$ radiations for the ^{65}Ga sing to the SLO (dash-dot-dotted curves), curves), and EGLO (solid curves) models and SLO model for M1 radiations (dotted of the calculated s-wave average radiation nding to the SLO model M1 function and mentioned E1 model functions. There are asured dipole γ-ray strength functions for , ^{64,66}Zn and ^{69}Ga nuclei [29–34], and the for the two nuclei from systematics of the measured data [13].

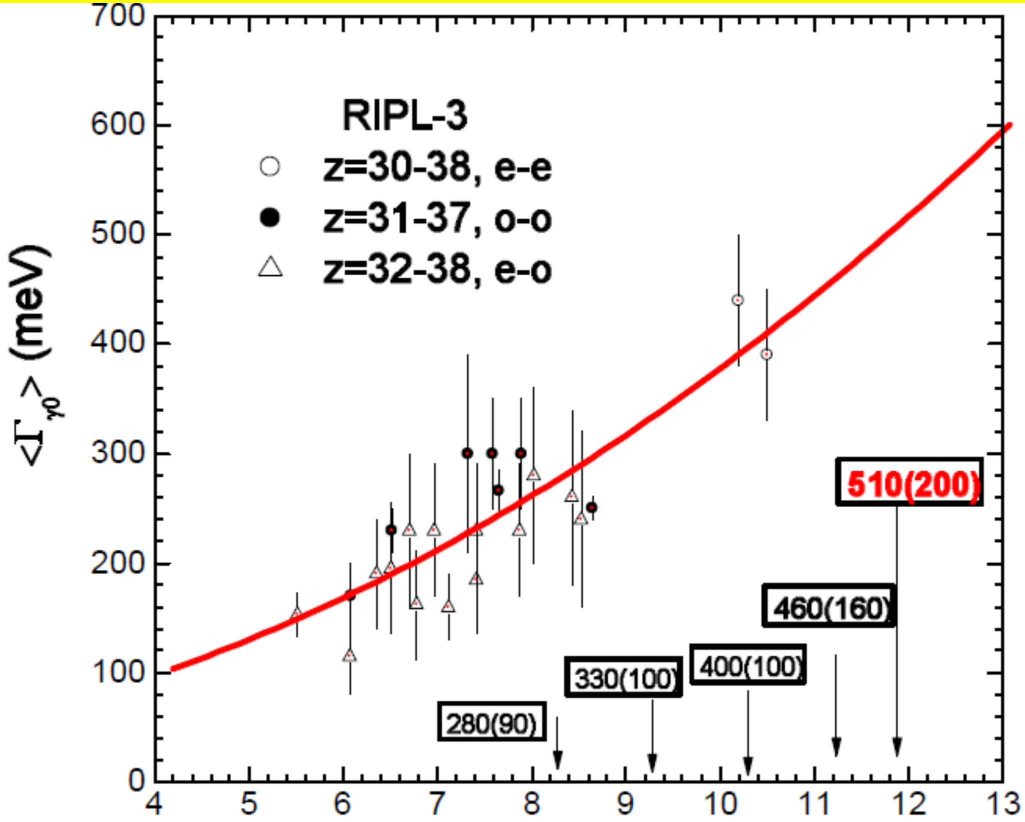
PRL **113,** 232502 (2014) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2014

Novel technique for Constraining r-Process (n, γ) Reaction Rates

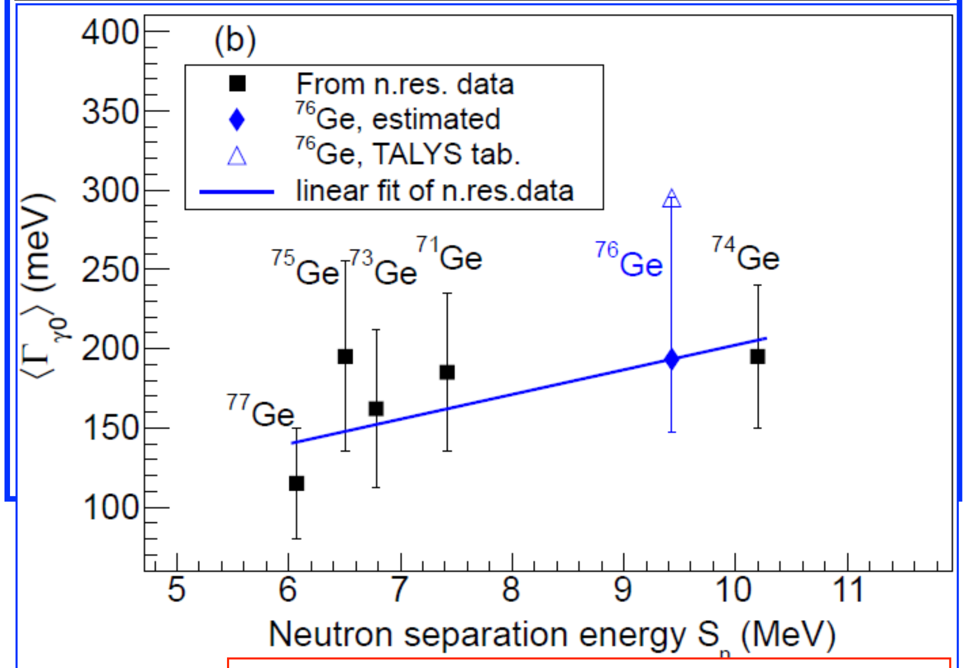




E1 RSF EGLO model and parameters for A~70 (2/4)



PRL 113, 232502 (2014) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2014



PHYSICAL REVIEW C **87**, 014319 (2013)

Transitional γ strength in Cd isotopes

A. C. Larsen,[1,*] I. E. Ruud,[1] A. Bürger,[1] S. Goriely,[2] M. Guttormsen,[1] A. Görgen,[1] T. W. Hagen,[1] S. Harissopulos
H. T. Nyhus,[1] T. Renstrøm,[1] A. Schiller,[4] S. Siem,[1] G. M. Tveten,[1] A. Voinov,[4] and M. Wiedeking[5]
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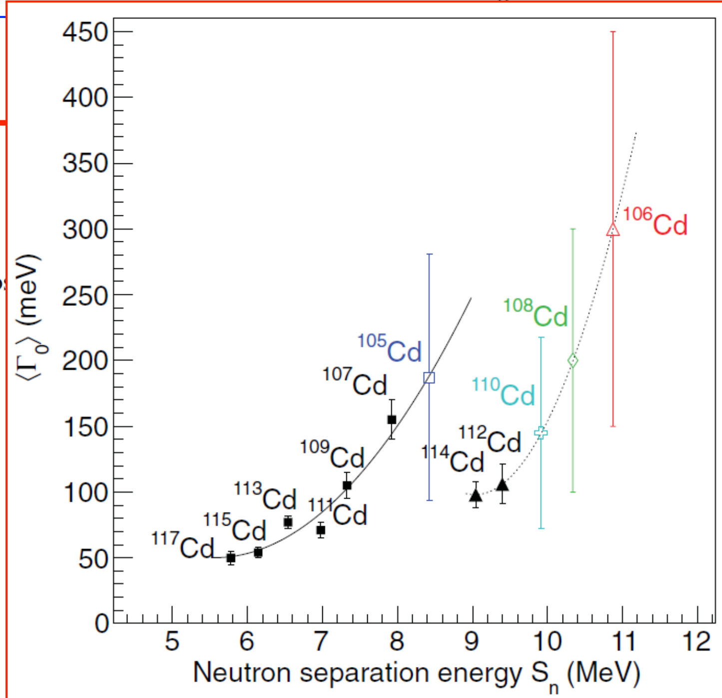
[2]*Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, CP 226, 1050 Brussels, Belgium*
[3]*Institute of Nuclear Physics, NCSR "Demokritos", 153.10 Aghia Paraskevi, Athens, Greece*
[4]*Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA*
[5]*iThemba LABS, P.O. Box 722, 7129 Somerset West, South Africa*

(Received 30 November 2012; published 16 January 2013)

The level densities and γ-ray strength functions of ^{105,106,111,112}Cd have been extracted from particle-γ coincidence data using the Oslo method. The level densities are in very good agreement with known levels at low excitation energy. The γ-ray strength functions display no strong enhancement for low γ energies. However, more low-energy strength is apparent for ^{105,106}Cd than for ^{111,112}Cd. For γ energies above ≈4 MeV, there is evidence for some extra strength, similar to what has been previously observed for the Sn isotopes. The origin of this extra strength is unclear; it might be due to $E1$ and $M1$ transitions originating from neutron skin



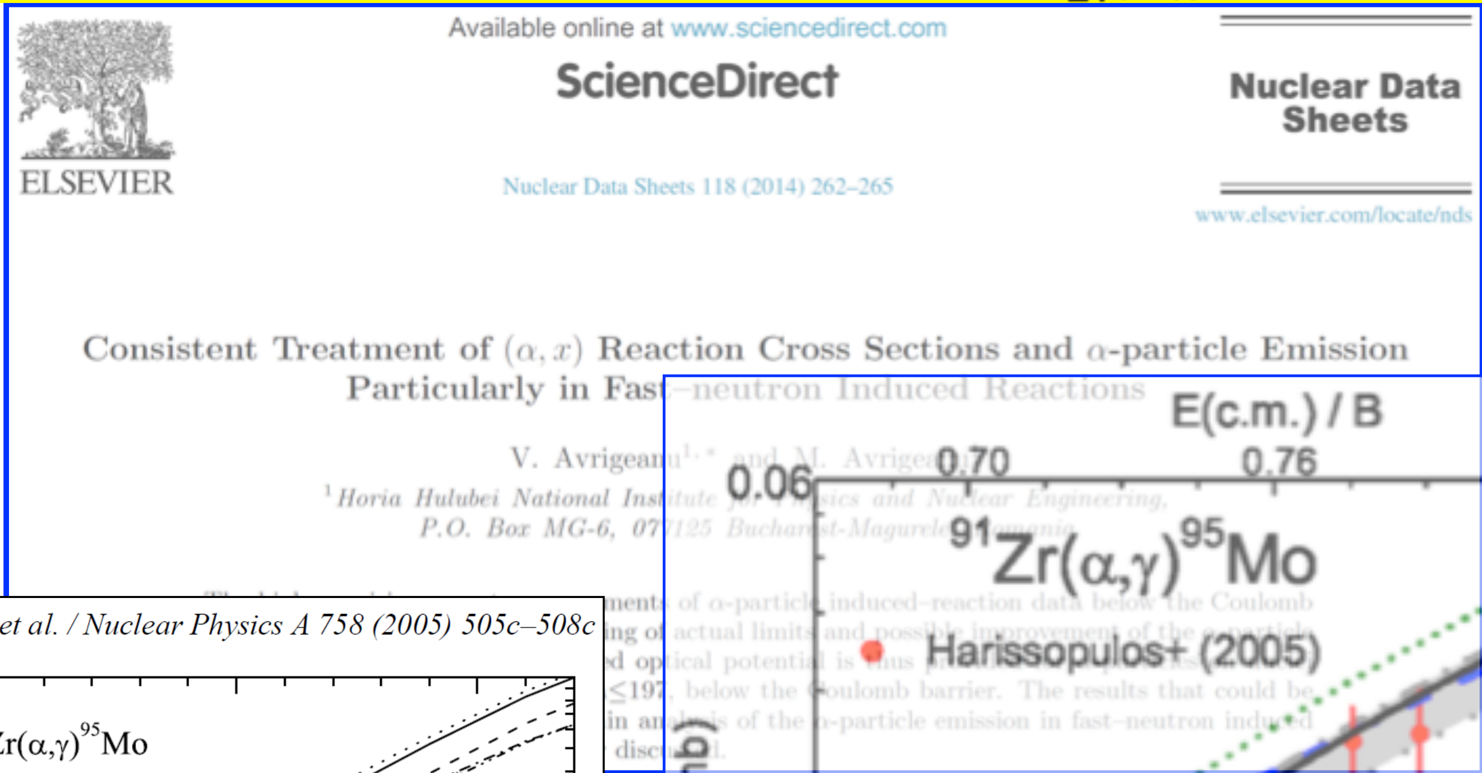
E1 RSF EGLO model and parameters for A~70 (3/4)

II. NUCLEAR MODEL PARAMETERS

TABLE I: Low-lying levels number N_d up to excitation energy E_d^* [12] used in cross-section SM calculations, the low-lying levels and *s*-wave nucleon-resonance spacings D_0^{exp} (Refs. [10, 13] for the superscripts *a* and *b*, respectively, with uncertainties given in parentheses, in units of the last digit) in the energy range ΔE above the separation energy S, for the target-nucleus ground state (g.s.) spin I_0, fitted to obtain the BSFG level-density parameter a and g.s. shift Δ (for a spin cutoff factor calculated with a variable moment of inertia [17] between half and 75% of the rigid-body value, from g.s. to S, and reduced radius r_0=1.25 fm), and the average radiation widths Γ_γ, either measured [13] or based on systematics (given between square brackets), and corresponding to the EGLO model parameter T_f=0.5 MeV used for description of the RSF data [28, 31].

Nucleus	N_d	E_d^*	Fitted low-lying levels and nucleon-resonance data						a	Δ	Γ_γ
			N_d	E_d^*	$S+\frac{\Delta E}{2}$	I_0	D_0^{exp}	Γ_γ			
		(MeV)		(MeV)	(MeV)		(keV)	(meV)	(MeV^{-1})	(MeV)	(meV)
^{61}Cu	36	3.092	32	3.019					6.55	-0.67	
^{63}Cu	60	3.291	79	3.565	9.026	0	5.9(7)^a		6.81	-0.85	
^{64}Cu	40	1.780	40	1.780	7.993	3/2	0.70(9)^b	490(30)	7.70	-1.55	
^{64}Zn	41	3.628	49	3.795					7.00	-0.03	
^{64}Ga	17	0.852	17	0.852					7.45	-2.10	
^{65}Cu	48	3.278	48	3.278					7.85	-0.10	
^{65}Zn	31	2.216	31	2.216	8.018	0	2.3(3)^b	726(60)	8.40	-0.60	
^{65}Ga	25	2.046	25	2.046	11.896			[510(200)]	8.00	-0.75	960
^{66}Cu	22	1.439	22	1.439	7.116	3/2	1.30(11)^b	385(20)	7.88	-1.40	
^{66}Zn	42	3.898	53	4.119					7.50	0.48	
^{66}Ga	28	0.974	34	1.076					8.00	-2.10	
^{66}Ge	4	2.173	4	2.173					7.50	0.55	
^{67}Cu	6	1.937	5	1.670					8.20	0.07	
^{67}Zn	31	1.875	26	1.783	7.278	0	4.62(55)^b	390(60)	8.04	-1.07	
^{67}Ga	28	2.282	28	2.282	8.420	0	2.5(2)^a		8.20	-0.55	
					11.226			[460(160)]			700
^{67}Ge	20	1.747	20	1.747					8.05	-0.95	
^{68}Zn	41	3.815	41	3.815	10.291	5/2	0.37(2)^b	440(60)	8.00	0.60	
^{68}Ga	41	1.350	51	1.548	8.278			[280(90)]	8.40	-1.70	304
^{68}Ge	16	3.087	16	3.087	12.392			[550(200)]	8.30	0.72	605
^{69}Zn	26	1.983	26	1.983	6.665	0	5.56(43)^b	320(40)	8.75	-0.63	
^{69}Ga	22	2.251	22	2.251	10.313			[400(100)]	8.75	-0.22	385
^{70}Zn	21	3.246	21	3.246					8.50	0.72	
^{70}Ga	31	1.372	38	1.534	7.654	3/2	0.316(41)^b	266(20)	9.00	-1.27	
^{71}Ga	22	2.082	22	2.082	9.300			[330(100)]	9.10	-0.30	250

Calculated (α,γ) reaction cross-section sensitivity vs. $f_{E1}(E\gamma)$ (4/4)


Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Nuclear Data Sheets
Nuclear Data Sheets 118 (2014) 262–265
www.elsevier.com/locate/nds

Consistent Treatment of (α, x) Reaction Cross Sections and α-particle Emission Particularly in Fast-neutron Induced Reactions

V. Avrigeanu[1,*] and M. Avrigeanu
[1] Horia Hulubei National Institute for Physics and Nuclear Engineering, P.O. Box MG-6, 077125 Bucharest-Magurele, Romania

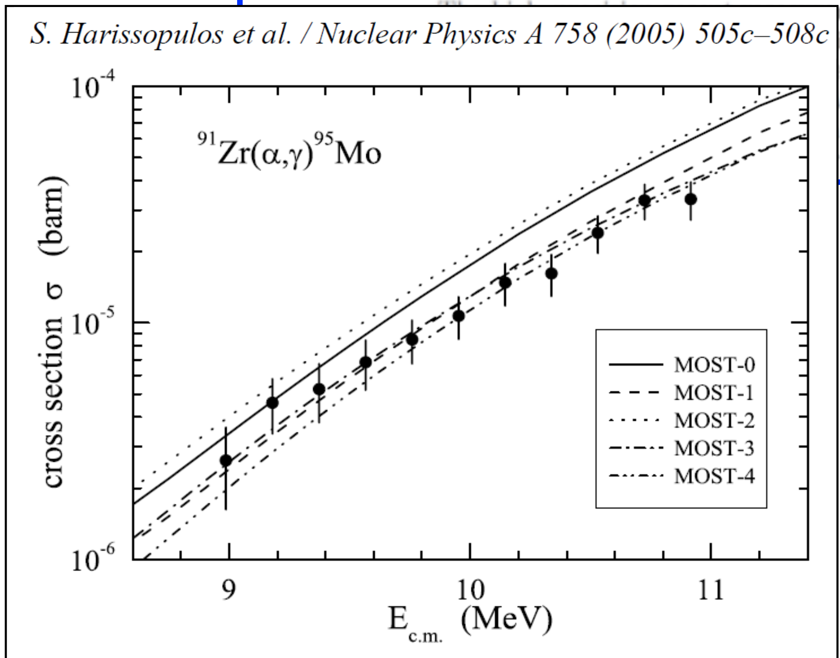
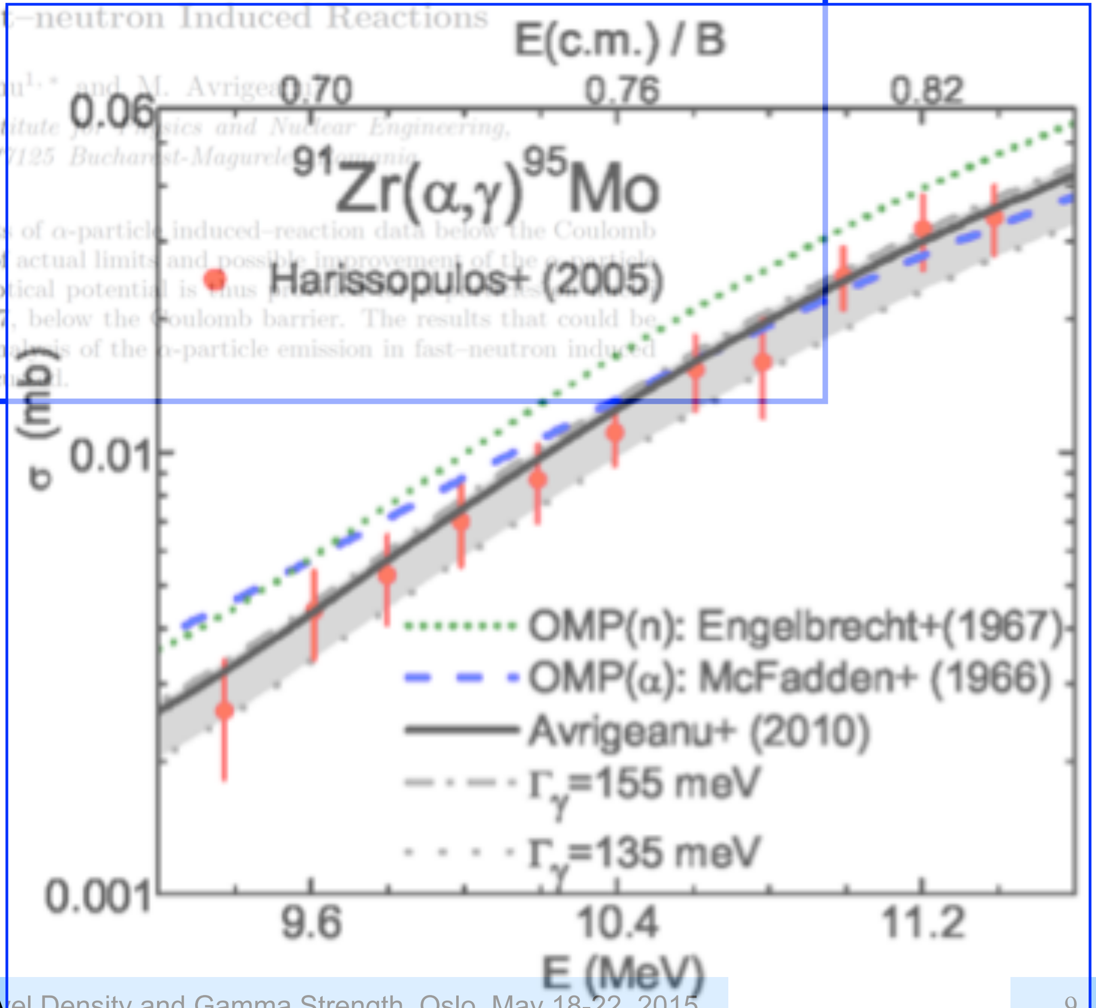


Figure 5. Cross sections measured for the $^{91}Zr(\alpha,\gamma)^{95}Mo$ reaction.



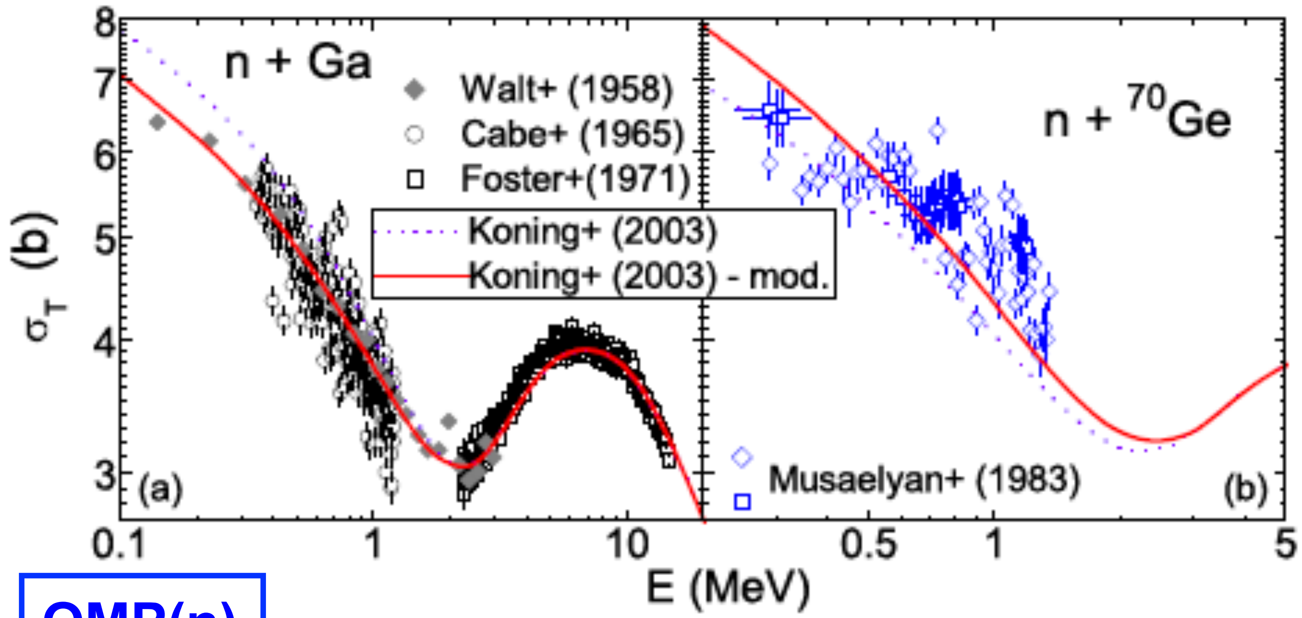
3. RSF effects on calculated c.s. of reactions with incident / emitted α's (1/7)

NLD

II. NUCLEAR MODEL PARAMETERS

TABLE I: Low-lying levels number N_d up to excitation energy E_d^* [12] used in cross-section calculations, the levels and s-wave nucleon–resonance spacings D_0^{exp} (Refs. [10, 13] for the superscripts *a* and *b*, respectively, with uncertainties given in parentheses, in units of the last digit) in the energy range ΔE above the separation energy S, for the target–nucleus ground state (g.s.) spin I_0, fitted to obtain the BSFG level–density parameter a and g.s. shift Δ (for a spin cutoff factor calculated with a variable moment of inertia [17] between half and 75% of the rigid-body value, from g.s. to S, and reduced radius r_0=1.25 fm), and the average radiation widths Γ_γ, either measured [13] or based on systematics (given between square brackets), and corresponding to the EGLO model parameter T_f=0.5 MeV used for description of the RSF data [28, 31].

Nucleus	N_d	E_d^* (MeV)	N_d	E_d^* (Me
^{61}Cu	36	3.092	32	3.01
^{63}Cu	60	3.291	79	3.56
^{64}Cu	40	1.780	40	1.78
^{64}Zn	41	3.628	49	3.79
^{64}Ga	17	0.852	17	0.85
^{65}Cu	48	3.278	48	3.27
^{65}Zn	31	2.216	31	2.21
^{65}Ga	25	2.046	25	2.04
^{66}Cu	22	1.439	22	1.43
^{66}Zn	42	3.898	53	4.11
^{66}Ga	28	0.974	34	1.07
^{66}Ge	4	2.173	4	2.17
^{67}Cu	6	1.937	5	1.67
^{67}Zn	31	1.875	26	1.78
^{67}Ga	28	2.282	28	2.28
^{67}Ge	20	1.747	20	1.74
^{68}Zn	41	3.815	41	3.81
^{68}Ga	41	1.350	51	1.54
^{68}Ge	16	3.087	16	3.08
^{69}Zn	26	1.983	26	1.98
^{69}Ga	22	2.251	22	2.25
^{70}Zn	21	3.246	21	3.24
^{70}Ga	31	1.372	38	1.53
^{71}Ga	22	2.082	22	2.08

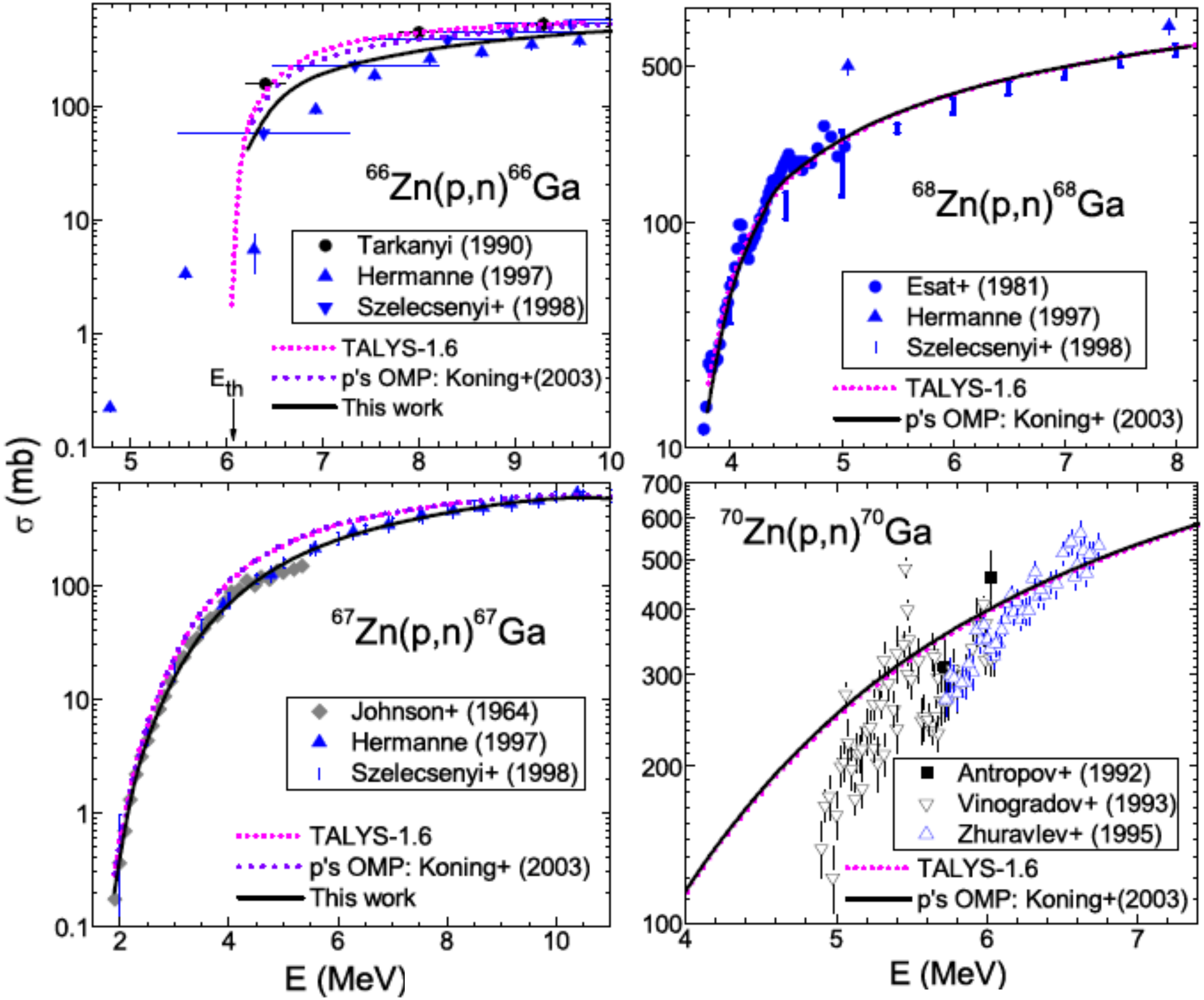


OMP(n)

FIG. 1: (Color online) Comparison of measured [11] and calculated neutron total cross sections for Ga and ^{70}Ge, using either (a) the local ^{69}Ga or (b) the global OMP parameters sets of Koning and Delaroche [18] (dotted curves), and additionally the energy–dependent geometry parameters mentioned in the text (solid curves).

RSF effects on calculated c.s. of reactions with incident / emitted α's (2/7)

OMP(p)



RSF effects on calculated c.s. of reactions with incident / emitted α's (3/7)

RSF

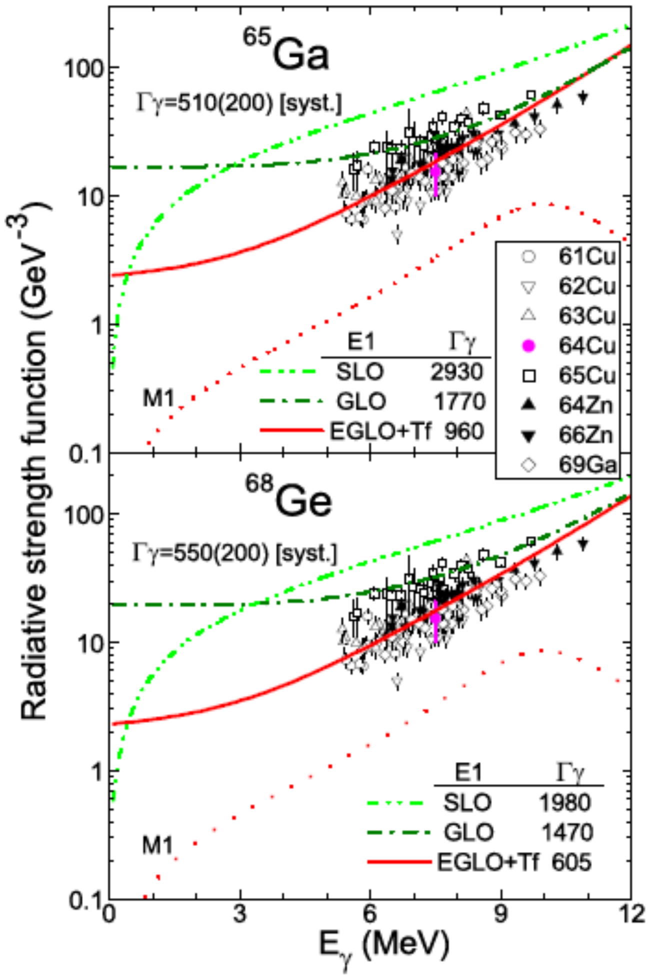


FIG. 3: (Color online) Comparison of calculated γ-ray strength functions of the $E1$ and $M1$ radiations for the ^{65}Ga and ^{68}Ge nuclei, using to the SLO (dash-dot-dotted curves), GLO (dash-dotted curves), and EGLO (solid curves) models for E1 radiations, and SLO model for M1 radiations (dotted curves), as well as of the calculated s-wave average radiation widths Γ_γ corresponding to the SLO model M1 function and each of the above–mentioned E1 model functions. There are also shown the measured dipole γ-ray strength functions for the ^{61,62,63,64,65}Cu, ^{64,66}Zn and ^{69}Ga nuclei [29–34], and the Γ_γ values deduced for the two nuclei from systematics of the measured data [13].

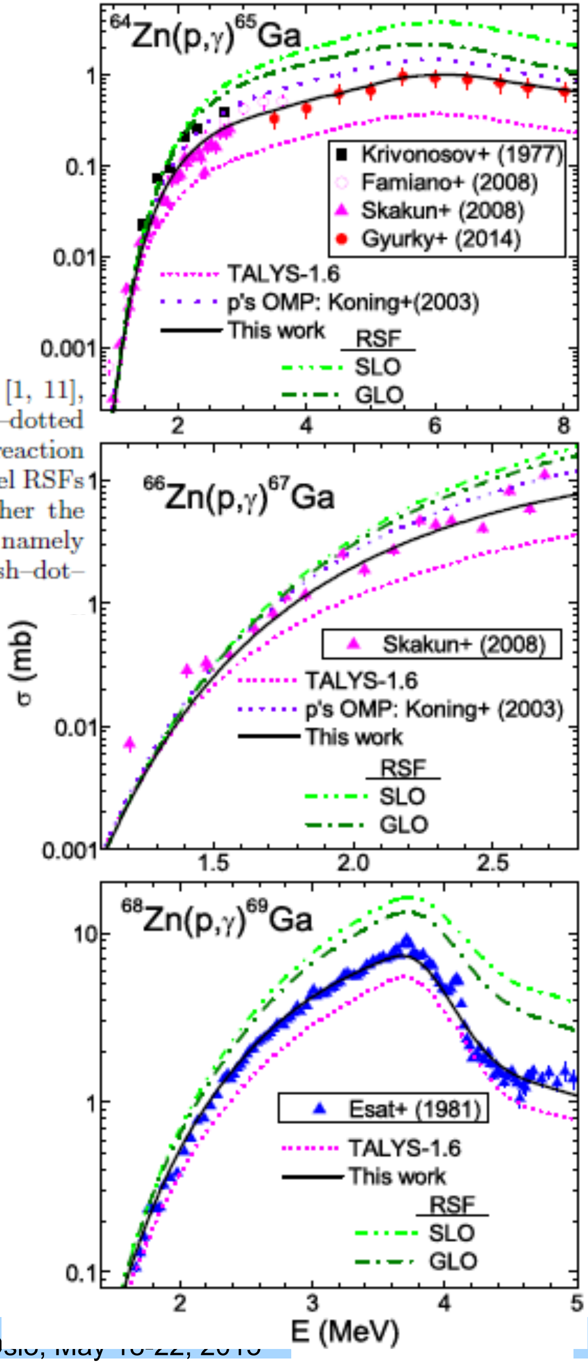


FIG. 4: (Color online) Comparison of the measured [1, 11], global predictions of the code TALYS [15] (short–dotted curves), and calculated cross sections for the (p,γ) reaction on ^{64,66,68}Zn using the proton OMPs and EGLO–model RSFs given in the text, with alternate involvement of either the global OMP [18] (dotted curves) or different RSFs, namely the GLO– (dash–dotted curves) or SLO–model (dash–dot–dotted curves) RSFs.

RSF effects on calculated c.s. of reactions with incident / emitted α's (4/7)

OMP(α)

PHYSICAL REVIEW C **90**, 044612 (2014)

Further explorations of the α-particle optical model potential at low energies for the mass range $A \approx 45$–209

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(Received 20 April 2014; revised manuscript received 2 October 2014; published 31 October 2014)

The recent high-precision measurements of α-particle-induced-reaction data below the Coulomb barrier (B) make possible the understanding of limits and possib (OMP) for α particles on nuclei within the mass numbe C **82**, 014606 (2010)]. An updated version of this pote increased surface imaginary-potential depth well below cross sections for well-deformed nuclei is removed by of this spherical OMP. Improved input parameters base functions, but no empirical rescaling factor of the γ an model calculation of the corresponding (α,x) reaction c

DOI: 10.1103/PhysRevC.90.044612 PA

[85] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevC.90.044612 for OMP parameters for nuclei involved in Refs. [15,16] and the present work, as well as tabular forms for the use within the EMPIRE-II [60] and TALYS [84] codes.

[86] https://www-nds.iaea.org/RIPL-3/optical/om-parameter-u.dat, iref=9603-9678.

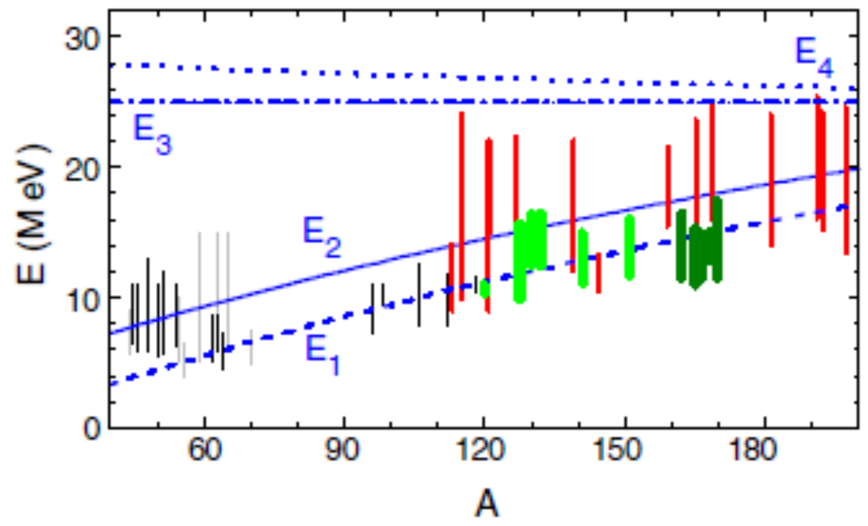
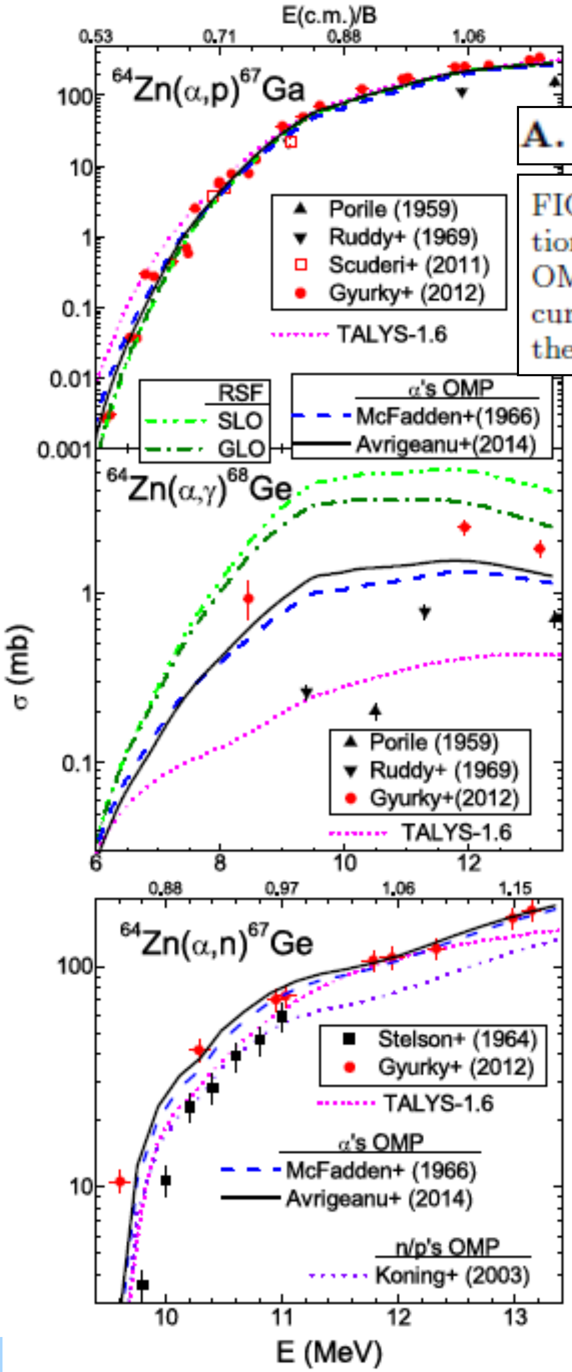


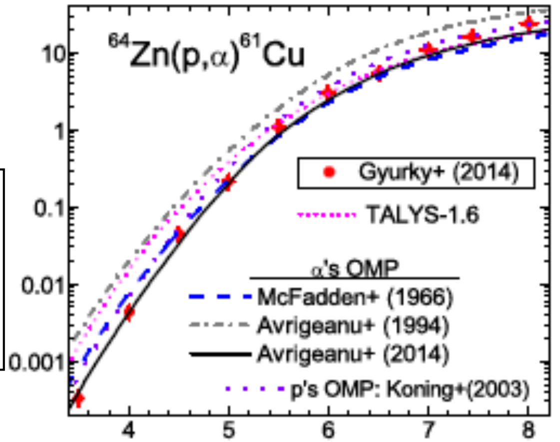
FIG. 1. (Color online) The A dependence of energies E_1 (dashed curve) below which the depth W_D is constant, E_2 (solid curve) corresponding to $0.9B$, E_3 (dash-dotted curve) and E_4 (dotted curve) given in Table II, and the energy ranges of the (α,x) reaction data involved in this work for $A \geqslant 120$ [5–14] (thick bars) as well as formerly for $A < 120$ [15] (thin bars), and $A > 113$ [16] (medium bars).

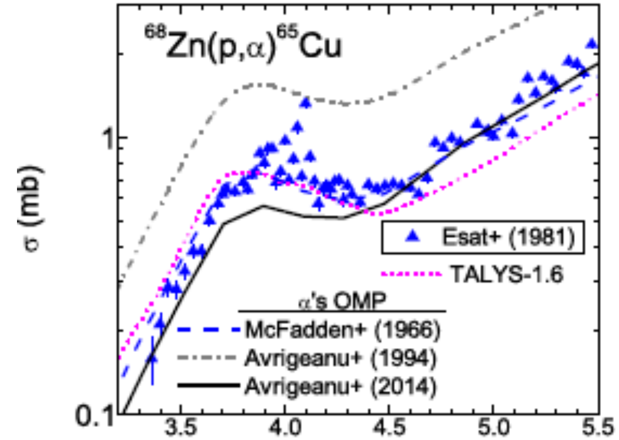
RSF effects on calculated c.s. of reactions with incident / emitted α's (5/7)



A. (α, x) reaction data analysis

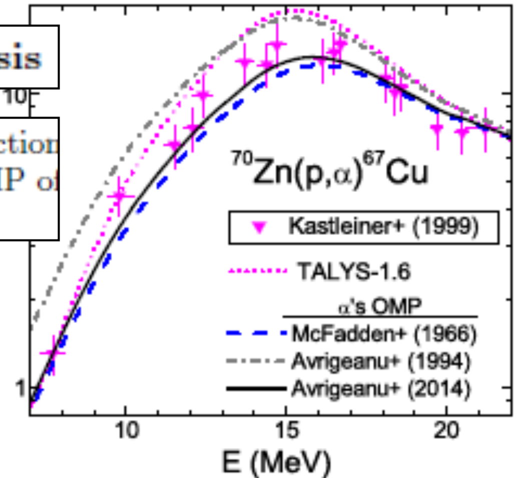
FIG. 5: (Color online) As Fig. 4 but for the α-induced reactions on ^{64}Zn [9, 11], calculated using the α-particle global OMPs of either Ref. [5] (dashed curves) or Ref. [3] (solid curves), and the alternate involvements done in the case of the latter α-particle OMP.





B. (p, α) reaction data analysis

FIG. 6: (Color online) As Fig. 5 but for the (p, α) reaction on ^{64,68,70}Zn, and the alternate use of the α-particle OMP of Ref. [2] (short dash–dotted curves).



RSF effects on calculated c.s. of reactions with incident / emitted α's (6/7)

FURTHE

TABL
neutron-r
given in p
a and gro
value, fro
the RSF d

Nucleus

^{113}In
^{116}Sn
^{116}Sb
^{117}Sb
^{120}Te
^{123}I
^{123}Xe
^{124}Xe
^{127}I
^{130}Xe
^{130}Cs
^{131}Cs
^{130}Ba
^{132}Ba
^{133}La
^{135}La
^{133}Ce
^{134}Ce
^{135}Ce
^{136}Ce
^{141}Pr
^{144}Nd
^{144}Pm
^{145}Pm
^{144}Sm
^{148}Sm
^{149}Sm
^{147}Eu
^{151}Eu
^{147}Gd
^{148}Gd
^{156}Gd
^{157}Gd
^{158}Gd
^{155}Tb
^{156}Tb
^{160}Dy
^{161}Dy
^{162}Dy
^{163}Dy
^{164}Dy
^{165}Ho
^{162}Er
^{166}Er
^{167}Er
^{168}Er
^{168}Tm
^{169}Tm
^{165}Yb
^{166}Yb

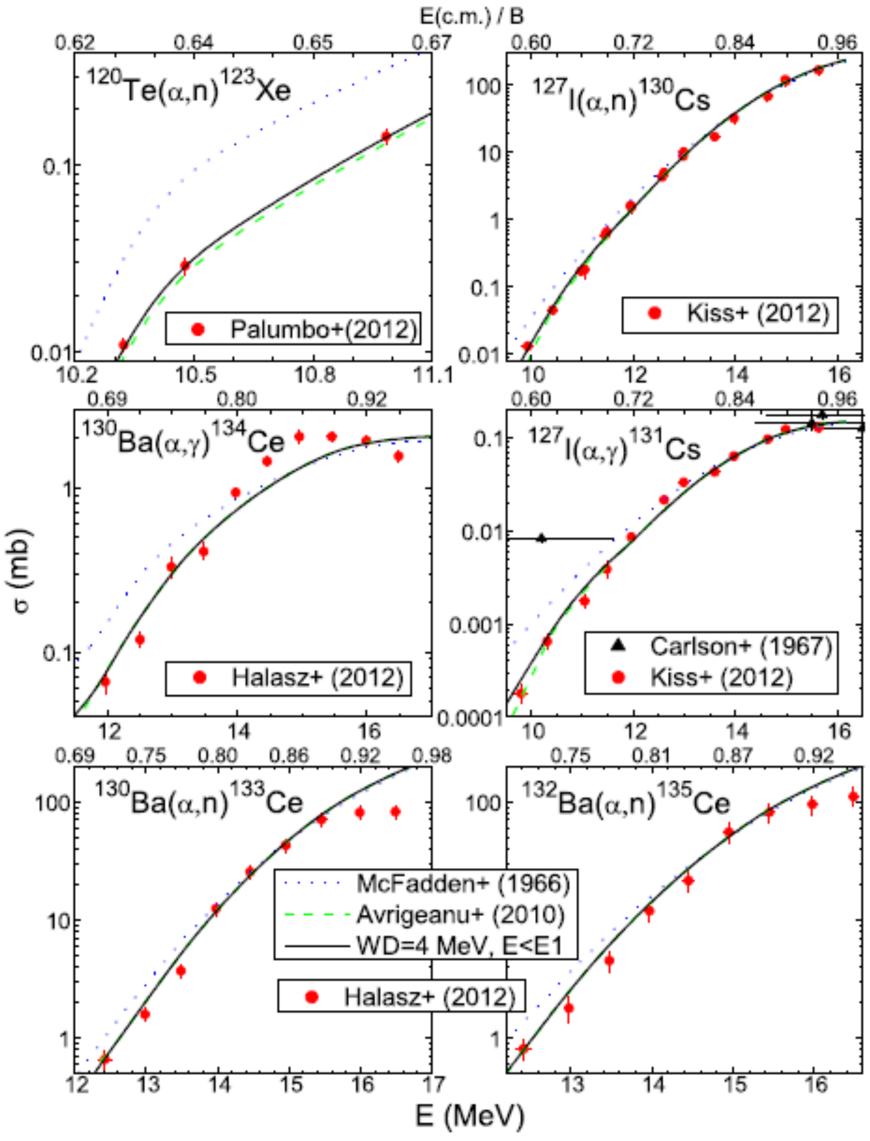
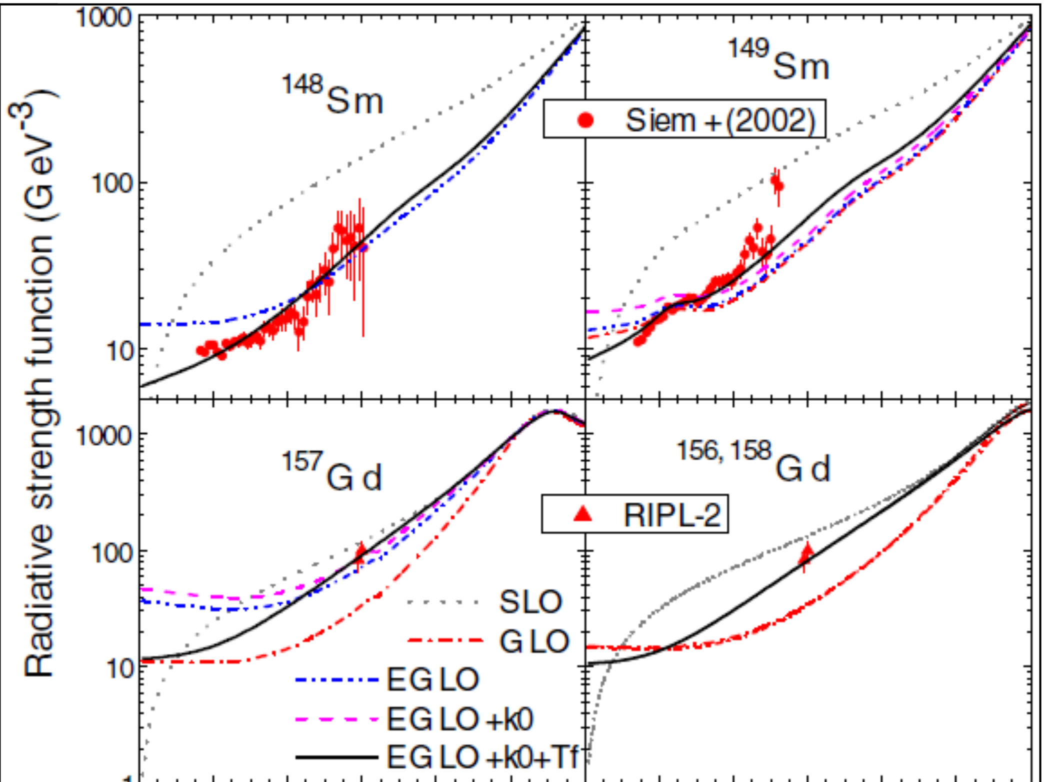


FIG. 4. (Color online) Comparison of former [40] and recently measured (α,x) reaction cross sections, for the target nuclei ^{120}Te [5], ^{127}I [6], and ^{130,132}Ba [7], and SM-calculated values using the α-particle OMPs of Refs. [33] (dotted curves), [16] (dashed curves), and Table II of this work (solid curves).



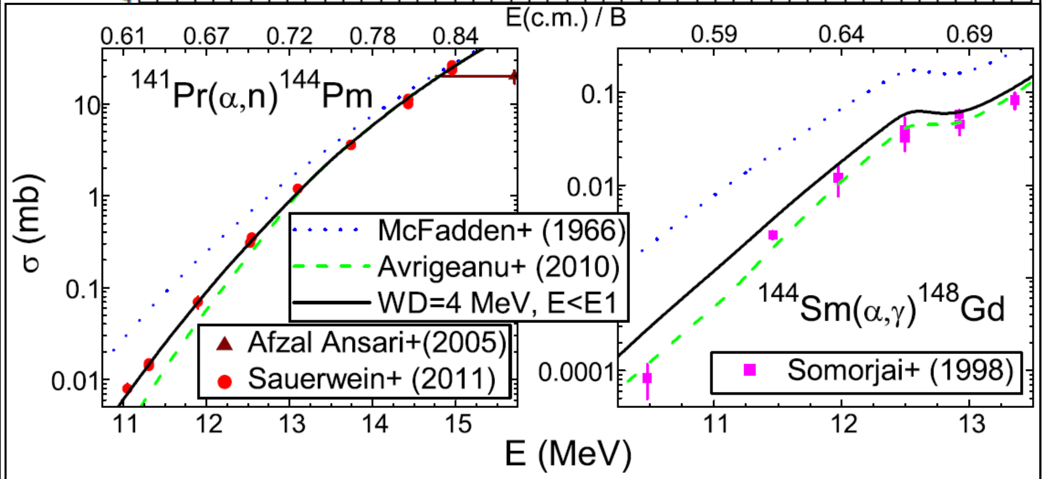


FIG. 5. (Color online) As Fig. 4 but for the target nuclei ^{141}Pr [8] and ^{144}Sm [34].

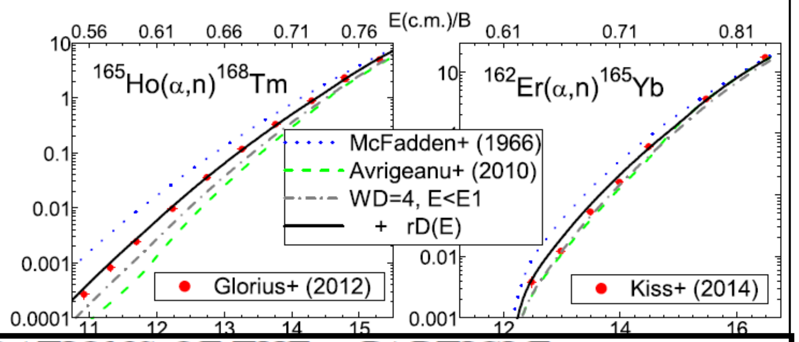
RSF effects on calculated c.s. of reactions with incident / emitted α's (7/7)

FURTHER EXPLORATIONS OF THE α-PARTICLE

TABLE I. Low-lying levels number N_d up to … neutron-resonance spacings D_0^{exp}, and average radiat… given in parentheses, in units of the last digit) [43] fo… α and ground-state shift Δ (for a spin cutoff factor c… value, from ground state to S, and reduced radius r_0… the RSF data [46,47] and Γ_γ values.

Nucleus	N_d	E_d^* (MeV)	Fitt… N_d	E_d^* (MeV)
^{113}In	33	1.768	33	1.768
^{116}Sn	17	2.844	26	3.106
^{116}Sb	22	0.881	22	0.881
^{117}Sb	17	1.536	17	1.536
^{120}Te	20	2.461	20	2.461

FURTHER EXPLORATIONS OF THE α-PARTICLE …



FURTHER EXPLORATIONS OF THE α-PARTICLE …

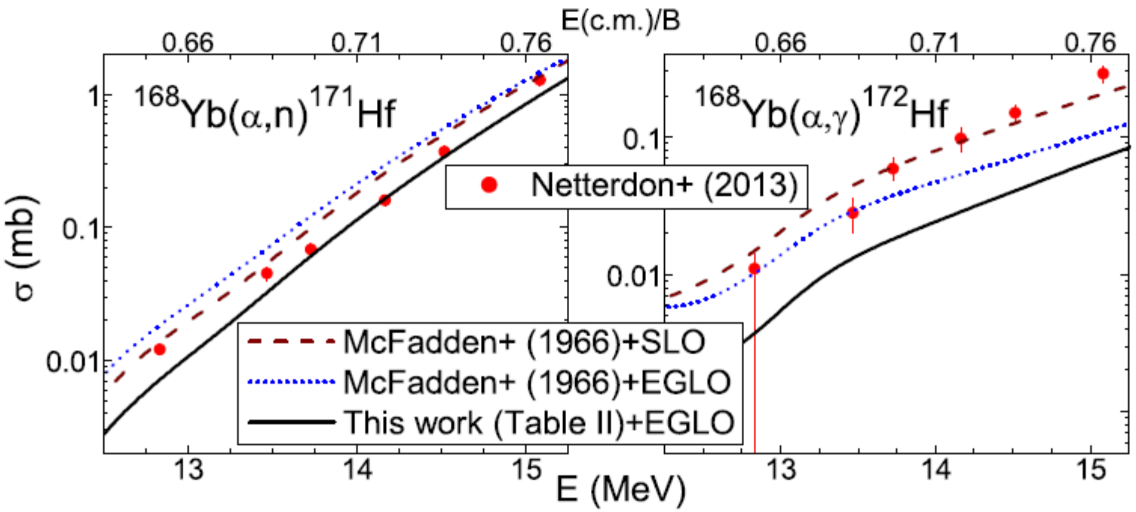
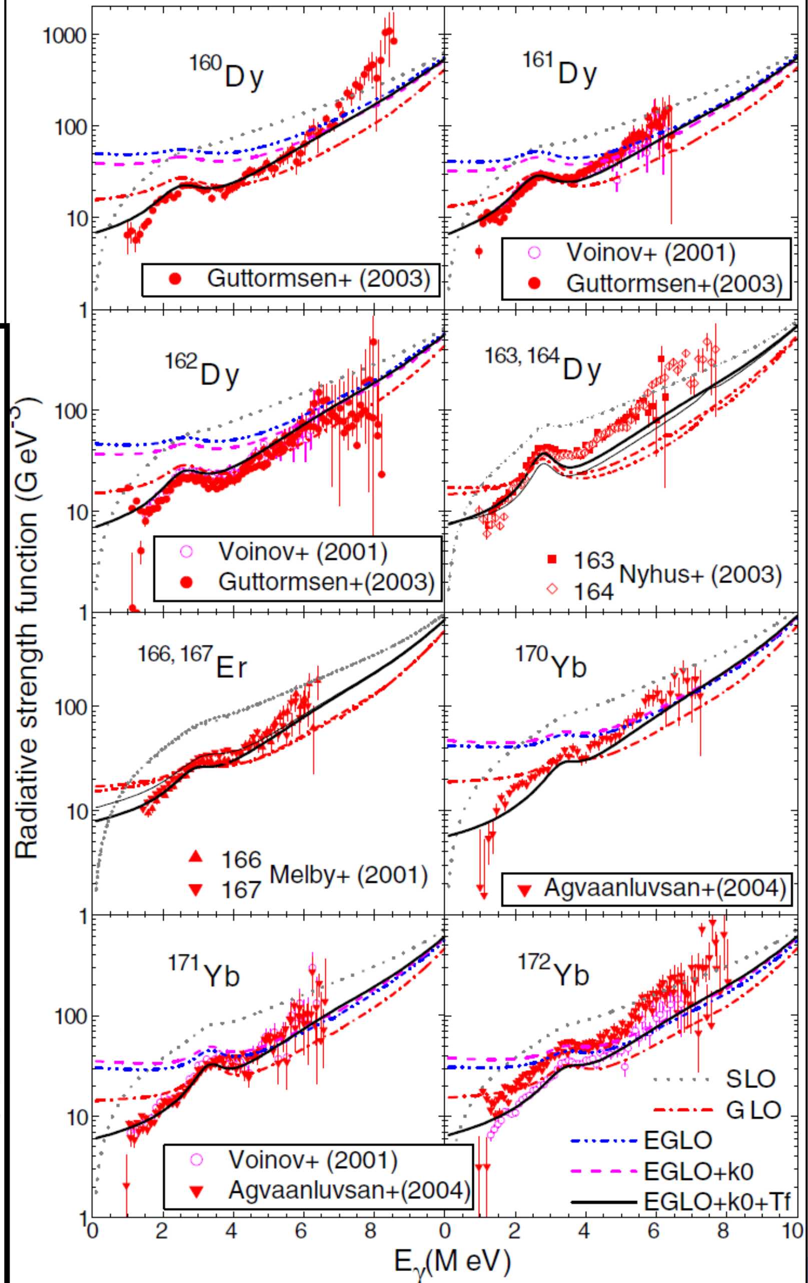


FIG. 11. (Color online) Comparison of the measured (α,n) and (α,γ) reaction cross sections for the target nucleus ^{168}Yb [14] and calculated values using the α-particle OMP of Ref. [33] and either the SLO (dashed curves) or EGLO (dotted curves) γ-ray strength functions, as well as the revised OMP of this work and the EGLO model (solid curves).

FURTHER EXPLORATIONS OF THE α-PARTICLE …



Conclusions (vs. 5^{th} Workshop, Oslo)

Thank you for your attention !

- **Results**
  - E1 RSF EGLO for A~70
  - Recent (α,γ), (p,γ), (p,α) reaction c.s. good description
  - RSF effects on calculated (α,γ) , (p,γ) on $^{64,66,68,70}Zn$
  - Consistent model input (NLD, OMP, RSF) ⟶ accurate α's OMP

- **Open Questions**
  - $f_{E1}(E\gamma)$ low-energy enhancement