TEST OF AVERAGE DESCRIPTION OF E1 GAMMA TRANSITIONS IN ATOMIC NUCLEI

V.A. Plujko[1,2], O.M. Gorbachenko[1],

E. P. Rovenskykh [1,2] , V.A. Zheltonozhskii [2]

[1] Taras Shevchenko National University, Kyiv, Ukraine

[2] Institute for Nuclear Research, Kyiv, Ukraine

The average probabilities of γ-transitions at γ -ray emission and photoabsorption can be described using the radiative (photon) strength functions (RSF). These functions are involved in calculations of the observed characteristics of most nuclear reactions. They are also used for investigation of nuclear structure (nuclear deformations, energies and widths of the giant dipole resonances, contribution of velocity-dependent force, shape-transitions, etc.) as well as in studies of nuclear reaction mechanisms.

ISINN-21, Alushta, Ukraine, May 20 –25, 2013

Radiative strength functions (RSF=PSF=GSF)

$$\vec{f}_{\alpha\lambda}(E_\gamma) = F_{\alpha\lambda}\left(E_\gamma, T_i\right), \qquad \overleftarrow{f}_{\alpha\lambda}(E_\gamma) = F_{\alpha\lambda}(E_\gamma, T_f), \qquad T_f = \varphi(T_i, E_\gamma)$$

$$\sigma_{E1}(E_\gamma) = 3E_\gamma \left(\pi\hbar c\right)^2 \vec{f}_{E1}\left(E_\gamma\right)$$

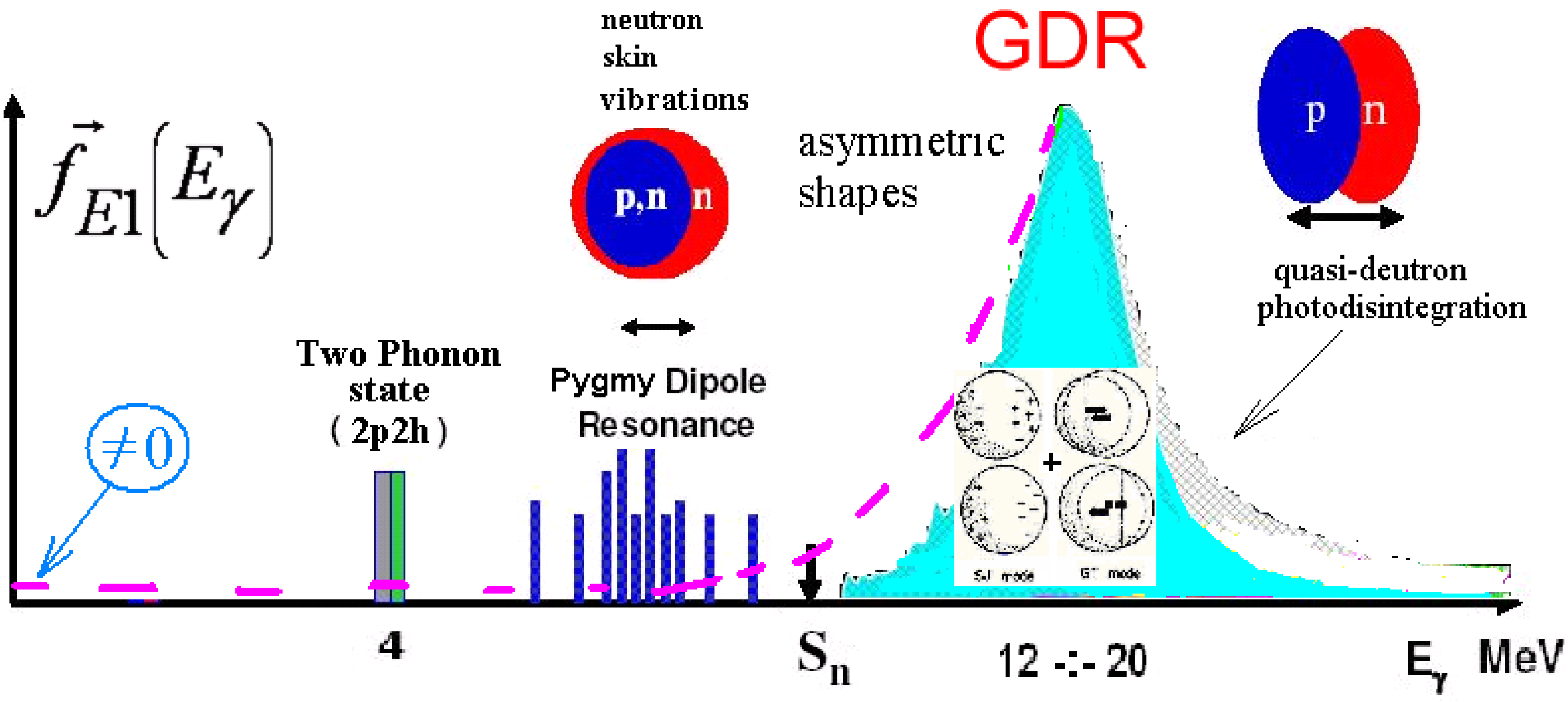
$$\frac{d\Gamma_{E1}\left(E_\gamma\right)}{dE_\gamma} = 3\,E_\gamma{}^3\ \overleftarrow{f}_{E1}\left(E_\gamma\right)\frac{\rho_f\left(U_f = U_i - E_\gamma\right)}{\rho_i\left(U_i\right)}$$

$$T_{E1}(E_\gamma) \sim 2\pi E_\gamma^3 \overleftarrow{f}_{E1}(E_\gamma)$$

Pecularities of Gamma-Transitions

Dipole electric gamma-transitions are dominant, if they take place together with multipole transitions of other order and types . Therefore we focus here on the E1 RSF.

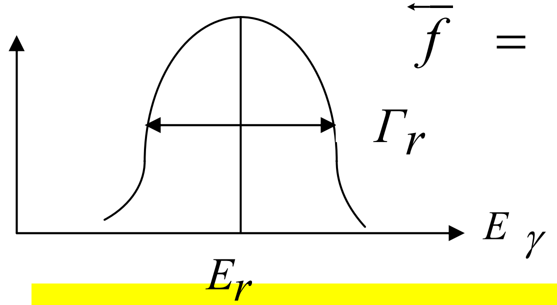
GENERAL SHAPE OF ELECTRIC DIPOLE RSF



Different RSF closed-forms

Standard Lorentzian (SLO)

[D. Brink. PhD Thesis(1955); P. Axel. PR 126(1962)]



$$\overleftarrow{f} = \overrightarrow{f} \sim \frac{E_\gamma \Gamma_r^2}{(E_\gamma^2 - E_r^2)^2 + E_\gamma \Gamma_r^2} \underset{E_\gamma \to 0}{\Rightarrow} 0$$

$$\Gamma_r = const \neq \varphi(E_\gamma) \sim 5\, MeV \; (T = 0)$$

Enhanced Generalized Lorentzian (EGLO)

[J. Kopecky , M. Uhl, PRC47(1993)] based on
S. Kadmensky, V. Markushev, W.Furman, Sov.J.N.Phys 37(1983)]

$$\overleftarrow{f} = \frac{E_\gamma \Gamma(E_\gamma, T_f)}{(E_\gamma^2 - E_r^2)^2 + E_\gamma^2 \Gamma_\gamma^2(E_\gamma, T_f)} + \frac{0.7\Gamma(E_\gamma = 0, T_i)}{E_r^3}$$

$$\overleftarrow{f} \Rightarrow const \neq 0 \; [E_\gamma \to 0]$$

$$T_f = \sqrt{\frac{U - E_\gamma}{a}};$$

Infinite fermi- liquid (two-body dissipation)

$$\Gamma(E_\gamma, T_f) = \Gamma_r \frac{E_\gamma^2 + 4\pi T_f^2}{E_\gamma^2} \cdot K(E_\gamma)$$

$$K(E_\gamma) \rightarrow$$

empirical factor from fitting exp. data

Generalized Fermi liquid (GFL) model

(extended to GDR energies of gamma- rays)

[Mughabghab&Dunford]

$$\vec{f} = \overleftarrow{f} = 8.674 \cdot 10^{-8} \cdot \sigma_r \Gamma_r \frac{K_{GFL} \cdot E_r \Gamma_m}{\left(E_\gamma^2 - E_r^2\right) + K_{GFL}\left[\Gamma_m E_\gamma\right]^2}$$

$$\Gamma_m = \Gamma_{coll}\left(E_\gamma, T_f\right) + \Gamma_{dq}\left(E_\gamma\right)$$

$$\Gamma_{coll} \equiv C_{coll}\left(E_\gamma^2 + 4\pi^2 T_f^2\right) \qquad K_{GFL} = 0.63$$

"Fragmentation" component

$$\Gamma_{dq}\left(E_\gamma\right) = C_{dq} E_\gamma \left|\overline{\beta_2}\right| \sqrt{1 + \frac{E_2^+}{E_\gamma}}$$

Extension of expression for GDR damping via coupling with surface vibrations (J.Le Tournie, 1964,1965)

Weak points of these approximations:

$$\overleftarrow{f}_{E\lambda}^{\mathrm{models}} = F\left\{\overleftarrow{f}_{E\lambda}^{KMF}(E_\gamma \to 0),\ \overleftarrow{f}_{E\lambda}^{SLO}(E_r)\right\}$$

$$\Gamma\left(E_r, T\right) \;=>\; \Gamma\left(E_\gamma, T_f\right)\ ???$$

Inconsistence of RSF shape with general relation between gamma-decay RSF of heated nuclei and nuclear response function on electromagnetic field

(J.L.Egido, P.Ring, J.Phys.G:Nucl.Part.Phys.19(1993)1)

General expression for gamma-decay RSF within modified Lorentzian (MLO)

(Plujko et al)

$$\overleftarrow{f}\left(E_\gamma, T_f\right) = 8.674\cdot 10^{-8}\,\frac{1}{1-\exp\left(-E_\gamma / T_f\right)}\, s\left(\omega = \frac{E_\gamma}{\hbar}, T_f\right), \quad \mathrm{MeV}^{-3}$$

$$s\left(\omega, T_f\right) = -\,\mathrm{Im}\,\chi\left(\omega, T_f\right)/\pi$$

PECULARITIES

Presence of low-energy enhancement factor

$$N_{1p1h} \equiv \frac{1}{\hbar\omega}\int d\varepsilon_1 d\varepsilon_2 f_0\left(\varepsilon_1\right)\left(1-f_0\left(\varepsilon_2\right)\right)\delta\left(\varepsilon_1-\varepsilon_2+\hbar\omega\right) = \frac{1}{1-\exp\left(-E_\gamma/T_f\right)} = (E_\gamma \to 0) = \frac{T_i}{E_\gamma} \gg 1$$

Non-zero limit at $E_\gamma \to 0$

$$\overleftarrow{f}_{E1}(E_\gamma = 0, T_f = T_i) \sim \cdot T_i \cdot \mathrm{Im}\Phi_{E1}(+0) \neq 0, \qquad \mathrm{Im}\Phi_{XL}(\omega) \equiv \mathrm{Im}\,\chi_{XL}(\omega)/\omega$$

Photoexcitation strength functions (E1)

(Alhassid&al. for cold nuclei)

$$\overleftarrow{f}_{E1}\left(E_\gamma, T_i = 0\right) = -\frac{1}{\pi} 8.674 \cdot 10^{-8} \, \mathrm{Im}\, \chi\left(\omega = \frac{E_\gamma}{\hbar}, T_i = 0\right), \ \mathrm{MeV}^{-3}$$

Heated nuclei

$$\vec{f}_{E\lambda} = \vec{\Phi}\left(E_\gamma, T_i\right), \qquad \overleftarrow{f}_{E\lambda} = \overleftarrow{\Phi}(E_\gamma, T_f)$$

$T_i, \ T_f = \varphi(T_i, E_\gamma)$ **- the temperatures of initial and final states**

Response function within semiclassical Landau-Vlasov approach is used in approximation of one strong collective state

(spherical nuclei)

$$\mathrm{Im}\,\chi\left(\omega,T_f\right)\propto\frac{E_\gamma\Gamma\left(E_\gamma,T_f\right)}{\left(E_\gamma^2-E_r^2\right)^2+\left[\Gamma\left(E_\gamma,T_f\right)E_\gamma\right]^2}$$

$\Gamma\left(E_\gamma=\hbar\omega,T\right)$ **- parameter of line spreading ("energy-dependent width")**

There are many variants of derivations; see for references:

R. Capote et al Nucl.Data Sheets, 110(2009)3107;

V.A.Plujko, O.M. Gorbachenko, E.V.Kulich, Int.J.Mod.Phys. E18 (2009) 996

METHOD OF INDEPENDENT SOURCES OF LINE SPREADING

$$\Gamma\left(E_\gamma = \hbar\omega, T\right) = \Gamma_{coll}\left(E_\gamma = \hbar\omega, T\right) + \Gamma_{frag}$$

Energy-dependent component results from two-body scattering in external E1 field (spreading width)

$$\Gamma_{coll}\left(E_\gamma = \hbar\omega, T\right) = \sum_{j\geq 1} a_j E_\gamma^j + b\,g(T)$$ => GDR ->2p2h

Fragmentation (" almost energy-independent") component

Γ_{frag} => GDR -> 1p1h [wall formala] +β-vibrations

APPROXIMATION OF AXIALLY-DEFORMED NUCLEI

RSF for gamma-decay (MeV^{-3})

$$\overleftarrow{f}\left(E_\gamma, T\right) = \frac{8.674\cdot 10^{-8}}{1-\exp\left(-E_\gamma / T_f\right)} \cdot \sum_{j=1}^{2} \sigma_{r,j}\Gamma_{r,j} \frac{E_\gamma \Gamma_j\left(E_\gamma, T_f\right)}{\left(E_\gamma^2 - E_{r,j}^2\right)^2 + \left[\Gamma_j\left(E_\gamma, T_f\right) E_\gamma\right]^2}$$

RSF for photoabsorption on cold nuclei

$$\vec{f}_{E1}\left(E_\gamma\right) = 8.674\cdot 10^{-8} \sum_{j=1}^{2} \sigma_{r,j}\Gamma_{r,j} \frac{E_\gamma \Gamma_j(E_\gamma, 0)}{\left(E_\gamma^2 - E_{r,j}^2\right)^2 + \left[\Gamma_j(E_\gamma, 0)\cdot E_\gamma\right]^2}$$

Normalization condition for widths

$$\Gamma_j(E_\gamma = E_{r,j}, T = 0) = \Gamma_{r,j}$$

Energy-dependent width within MLO4

$$\Gamma_{r,j} = a_1 \cdot E_{r,j} + a_2 \cdot |\beta_2| \cdot E_{r,j} \cdot \gamma_j - \text{systematics}$$

$$\Gamma_j(E_\gamma, T) = b_j \cdot \{a_1 \cdot [E_\gamma + U(T)] + a_2 \cdot |\beta_2| \cdot E_{r,j} \cdot \gamma_j\}$$

$$\gamma_j = \begin{cases} 1, & \text{sph. nucl.} \\ \left(R_0 / R_j\right)^{1.6}, & \text{def. nucl. [B.Bush, Y.Alhassid, NPA 531 (1991) 27]} \end{cases}$$

$$|\beta_2| = \sqrt{1224 A^{-7/3} / E_{2_1^+}}$$ **- dynamical deformation**

[L. Esser, U. Neuneyer, R. F. Casten, P. von Brentano, PRC 55(1997) 206]

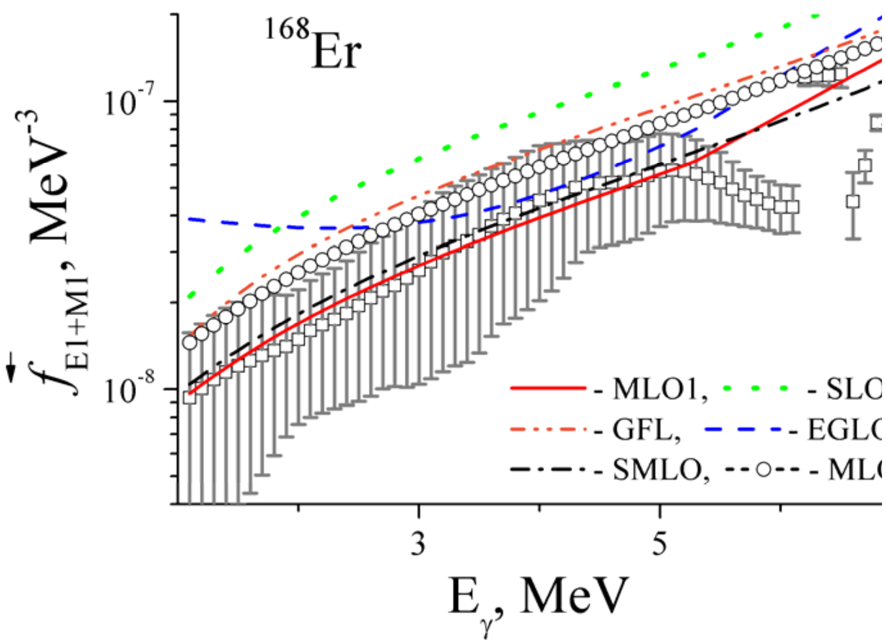
$E_{2_1^+}$ **from experimental data-base (RIPL3) or systematics by**

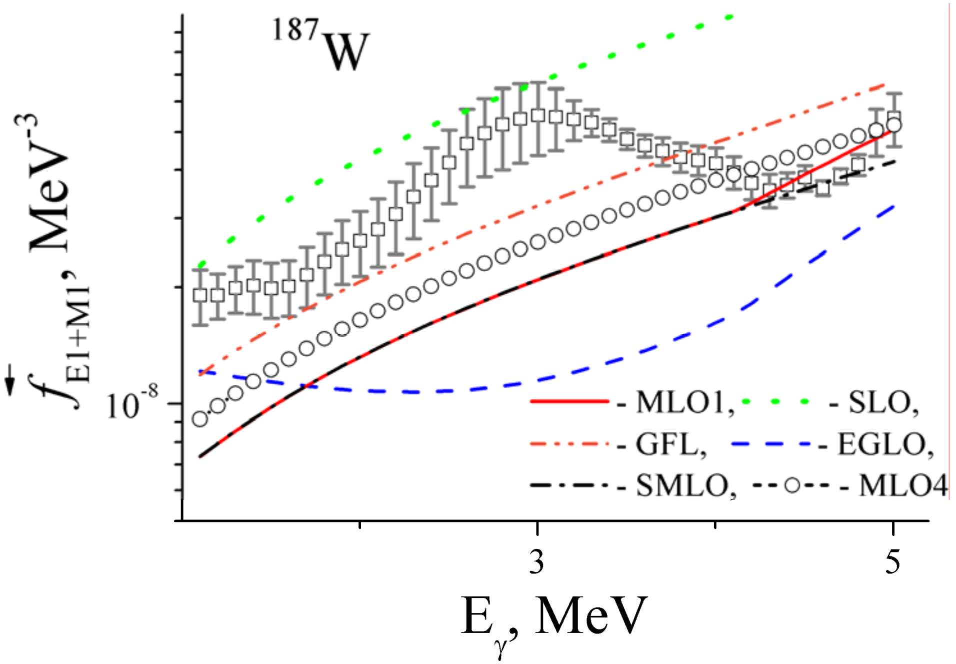
S.Hilaire, S.Goriely, NPA 779(2006)63:

$$E_{2_1^+} = 65 A^{-5/6} / (1 + 0.05 E_{shell})$$

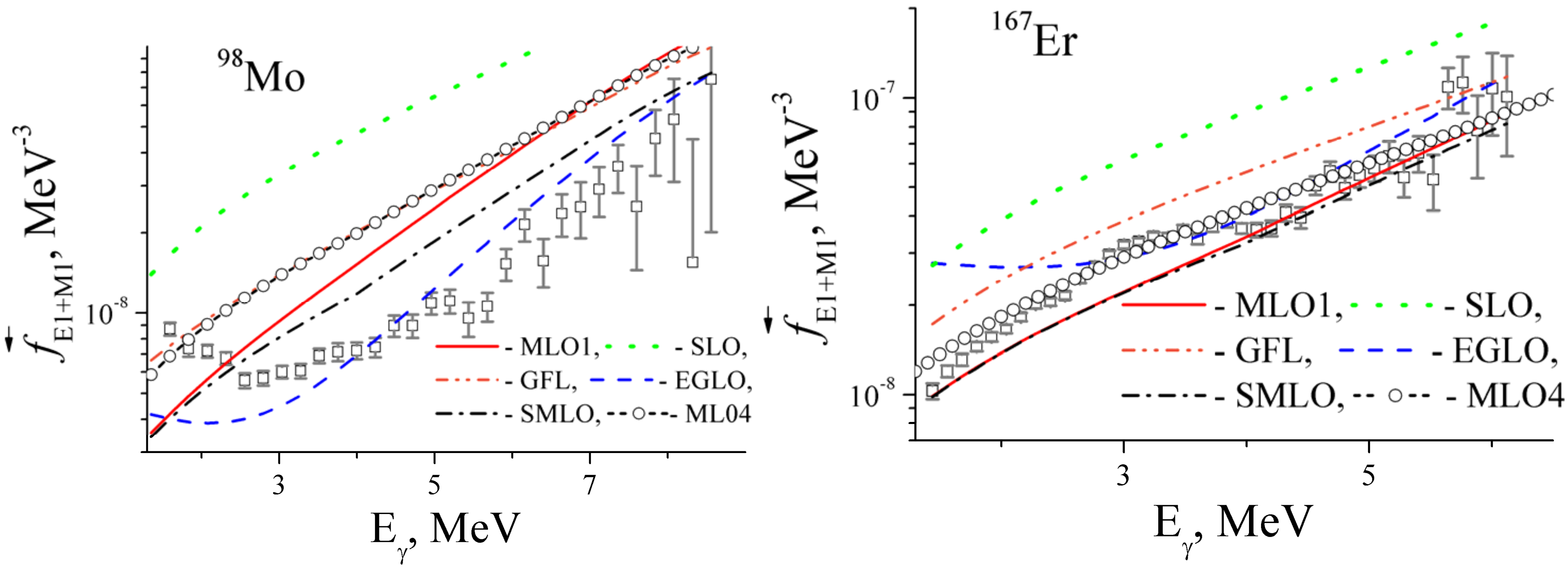
SLO, EGLO, GFL, MLO1-3, SMLO: $\beta_{2,eff} = \varphi(Q_2[\{\beta_j\}]$

Comparisons of gamma-decay RSF



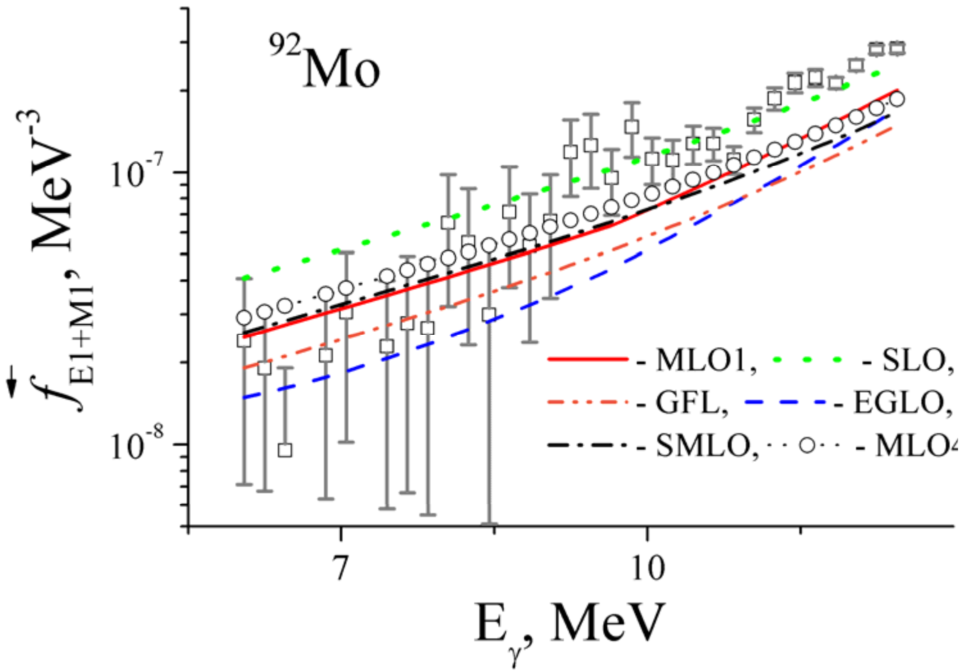


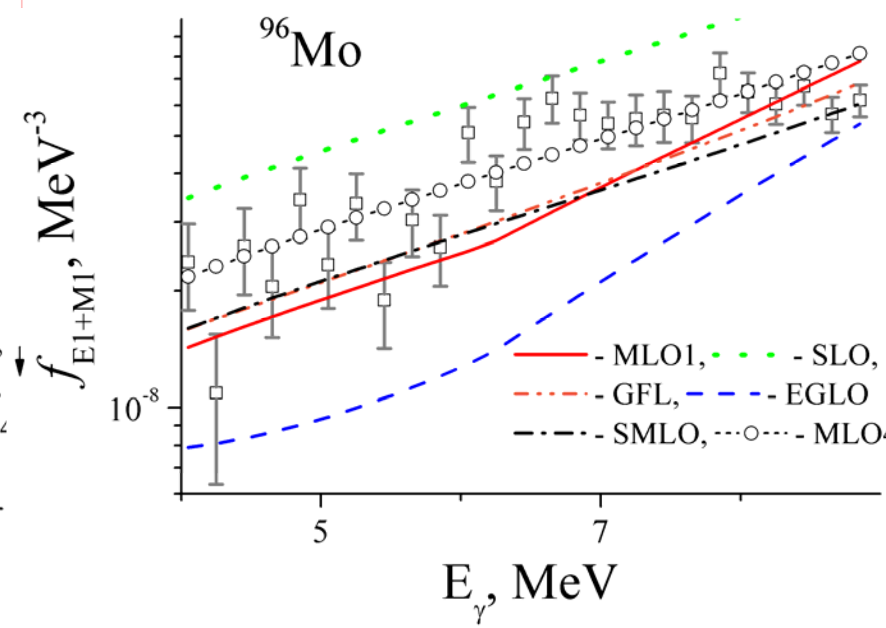
Comparisons of gamma-decay strength functions for ^{168}Er **and** ^{187}W **:**
$U = S_n$**; experimental data -- A.M. Sukhovoj et al. Izvestiya RAN. Seriya Fiz. 69, 641 (2005); A.M. Sukhovoj et al. in Proc. of the XV Int. Seminar on Interaction of Neutrons with Nuclei. (Dubna, May 2007), 92 (2007)**.



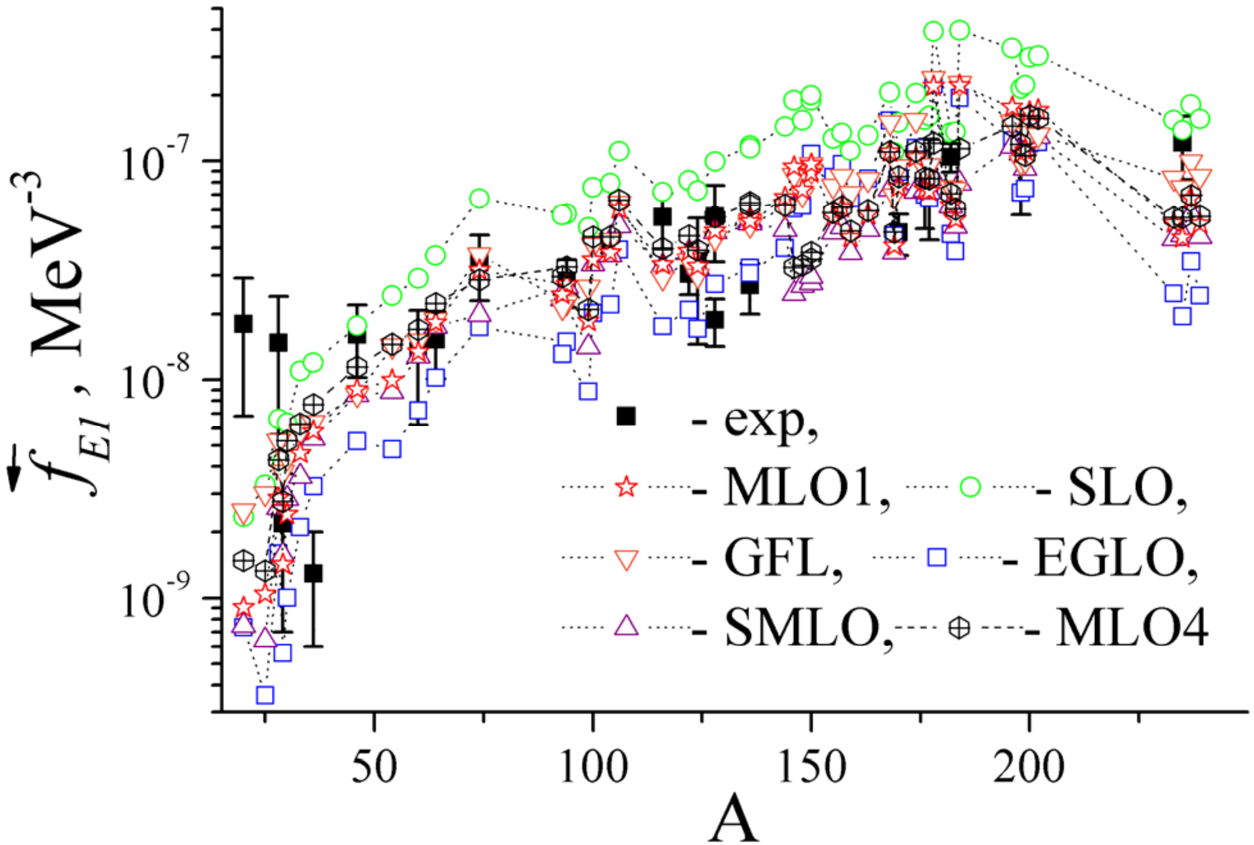
Comparisons of gamma-decay strength functions for ^{98}Mo **and** ^{167}Er **: experimental data --** E. Melby, M. Guttormsen, et al., Phys. Rev.C. 63, 044309 (2001); U. Agvaanluvsan, A. Schiller, et al., Phys. Rev.C. 70, 054611 (2004); http://www.mn.uio.no/fysikk/english/research/about/infrastructure/OCL/compilation/

$$\overleftarrow{f}_{aver}(E_\gamma) = \begin{cases} \dfrac{1}{S_n - 4} \displaystyle\int_4^{S_n} \overleftarrow{f}(E_\gamma, U_f = U_i - E_\gamma) dU_i, & 1 < E_\gamma \le 4, \\ \dfrac{1}{S_n - E_\gamma} \displaystyle\int_{E_\gamma}^{S_n} \overleftarrow{f}(E_\gamma, U_f = U_i - E_\gamma) dU_i, & 4 < E_\gamma \le S_n, \end{cases}$$





Comparisons of gamma-decay strength functions for ^{92}Mo and ^{96}Mo : $U = S_n$;experimental data -- R. Schwengner, G. Rusev, et al., Phys. Rev. C. 78 (2008) 064314; Phys. Rev. C. 81, 034319 (2010)

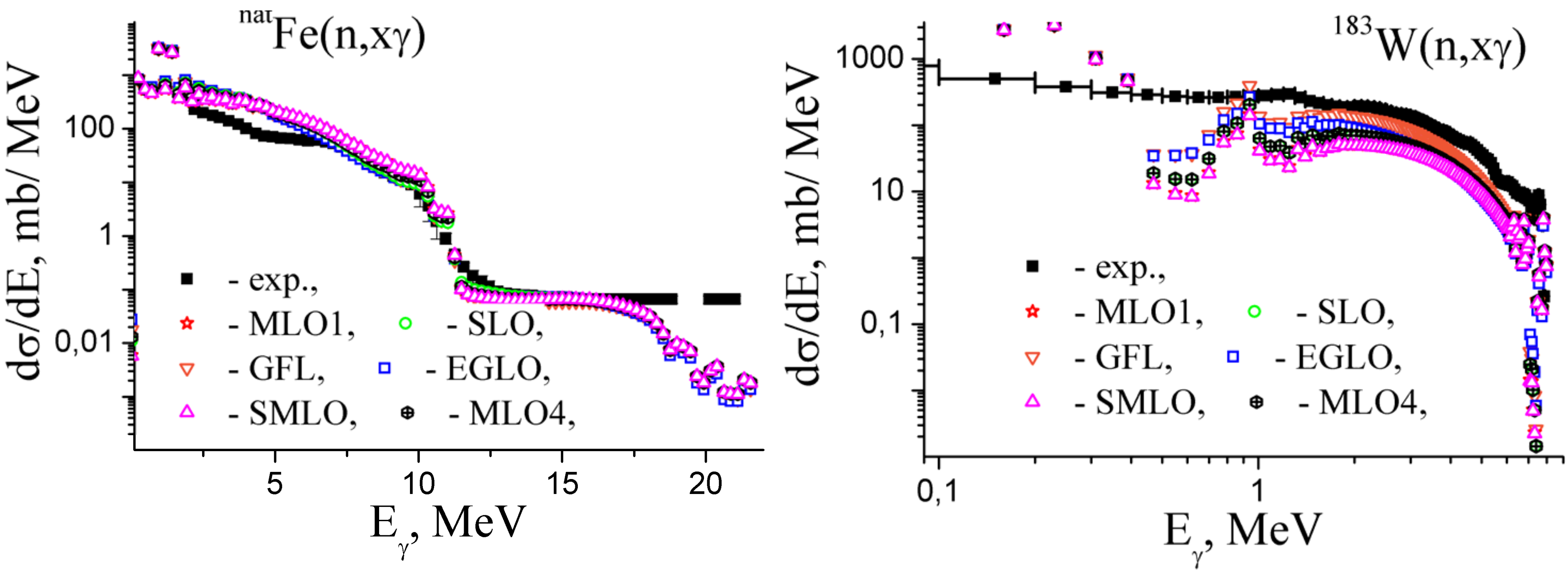


The gamma-decay strength functions within different RSF models: $U = S_n$. Experimental data are taken from J. Kopecky Handbook for calculations of nuclear reaction data. Reference Input Parameter Library (RIPL), Tech. Rep. IAEA-TECDOC-1034, Ch. 6, 1998; directory “Gamma” on the RIPL-1 web site at http://www-nds.iaea.or.at/ripl/

The average $\sum_{i=1}^{n}\left(\chi_i^2(model)/\chi_i^2(\mathrm{SLO})\right)/n$ ratio of chi-square deviations of the theoretical RSF of γ-decay from experimental data. n - number of nuclei

Exp.Data	n	Model				
		EGLO	GFL	MLO1	SMLO	MLO4
[1]	38	1,22	0,91	0,98	1,01	0,89
[2]	41	0,18	0,17	0,11	0,11	0,13
[3]	7	2,22	2,11	1,16	1,71	1,20
[4]	53	9,38	2,76	8,75	13,81	6,97

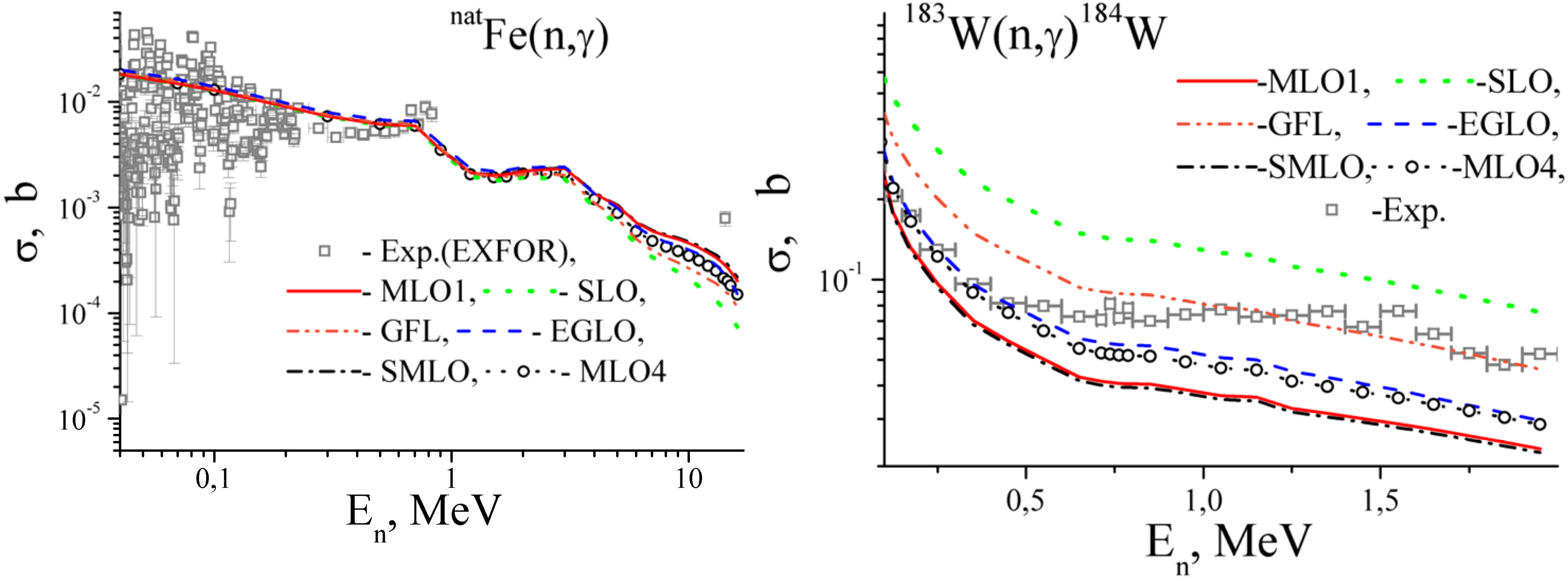
1. A.M. Sukhovoj et al. Izvestiya RAN. Seriya Fiz. **69**, 641 (2005); A.M. Sukhovoj et al. in Proc. of the XV Int. Seminar on Interaction of Neutrons with Nuclei. (Dubna, May 2007), 92 (2007).
2. E. Melby, M. Guttormsen, et al., Phys. Rev.C. **63**, 044309 (2001); U. Agvaanluvsan, A. Schiller, et al., Phys. Rev.C. **70**, 054611 (2004); http://www.mn.uio.no/fysikk/english/research/about/infrastructure/OCL/compilation/
3. R. Schwengner, G. Rusev, et al., Phys. Rev. C. 78 (2008) 064314; Phys. Rev. C. **81**, 034319 (2010)
4. J. Kopecky Handbook for calculations of nuclear reaction data. Reference Input Parameter Library (RIPL), Tech. Rep. IAEA-TECDOC-1034, Ch. 6, 1998; directory “Gamma” on the RIPL-1 web site at http://www-nds.iaea.or.at/ripl/



(*a*) (*b*)

Gamma-ray spectra from ${}^{nat}Fe(n,x\gamma)$ and ${}^{183}W(n,x\gamma)$ reactions calculated with EMPIRE code using different models for the RSF. The experimental data are taken from [1] for panel *a* ($E_n = 14.1\ MeV$) and from [2] for panel *b* ($E_n = 0.5\ MeV$)

1.V.M. Bondar et al., in Proc. of the 18th Int. Sem.onInter. of Neutrons with Nuclei ”Neutron Spectroscopy, Nuclear structure, Related topics” (Dubna, May, 2010). (2011) 135
2. J.Voignier et al., J. Nucl. Science and Engineering, **112**, 87 **(**1992)



(*a*) (*b*)

The excitation functions of $^{nat}Fe(n,\gamma)$ and $^{183}W(n,\gamma)^{184}W$ reactions using different RSF models. The experimental data are taken from EXFOR data library [1] for panel *a* and from [2] for panel *b*.

1. Experimental Nuclear Reaction Data (EXFOR); http://www.nndc.bnl.gov/exfor/exfor00.htm
2. R.L.Macklin, D.M. Drake, E.D. Arthur, J. Nucl. Science and Engineering **84**, 98 (1983)

SUMMARY

- **Rather reliable simple description of E1 gamma-decay strength can be obtained by the use of models with dependence of line spreading on gamma-ray&excitation energies. It seems that the MLO4 is best candidate for good overall description of the RSF.**

- **To better understand role of the temperature and energy dependence of the RSF, experimental data are necessary as functions of gamma-ray and excitation energies, especially at low gamma-ray energy.**

***R.Capote et al*, Nucl. Data Sheets 110 (2009) 310; http://www-nds.iaea.or.at/ripl3/;**
***V.A.Plujko, R.Capote, O.M. Gorbachenko,* At.Data Nucl.Data Tables 97(2011) 567;**
***V.A.Plujko, R.Capote, V.M.Bondar, O.M. Gorbachenko, J. Kor. Phys.Soc.* 59(2011) 1514**
***V.A.Plujko et al, Nucl. Phys. At.Energy 13(2012)341;* http:/jnpae.kinr.kiev.ua**

THANK YOU FOR ATTENTION !!!

Thriaxial Standard Lorentzian (TSLO)
[Dresden-Rossendorf approach]

$$\overleftarrow{f} = \overrightarrow{f} = f$$

$$f_{E1}\left(E_\gamma\right) = const \sum_{j=1}^{3} s_{r,j} \Gamma_{r,j} \frac{E_\gamma \Gamma_j}{\left(E_\gamma^2 - E_{r,j}^2\right)^2 + \left[\Gamma_j \cdot E_\gamma\right]^2}$$

$s_{r,j}$ => fixed by TRK sum rule

$$\mathrm{E}_{r,i} = \mathrm{E}_{r,0} \Phi_i(\beta,\gamma) - \text{SJ model}$$

$$\Gamma_{r,j} = \Gamma_{r,0}(R_0/R_i)^{1.6} \Rightarrow \text{Bush\&Alhassid}$$

$$\Gamma_{r,j} = \Gamma_{r,0}(\mathrm{E}_{r,i}/\mathrm{E}_0)^{1.6} \Rightarrow \text{GT model} + R_i = \text{const} / \mathrm{E}_{r,i} \text{ (SJ model)}$$

GENERAL SHAPE OF ENERGY-DEPENDENT WIDTH

$$\Gamma\left(E_\gamma = \hbar\omega, T\right) = a + \sum_{j\geq 1}^{n} b_j E_\gamma^j + cT^k$$

Energy-dependent component results from two-nucleon scattering in external E1 field (spreading width)

$$\text{GDR (1p1h coherent state)} -> \text{2p2h}$$

It caused by frequency dependence of energy conservation law for scattering in external field due to possibility of energy exchange between the particles and field

$$\delta\left(\Delta\varepsilon \equiv \varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4\right) \;=>\; \delta\left(\Delta\varepsilon \pm \hbar\omega\right)$$

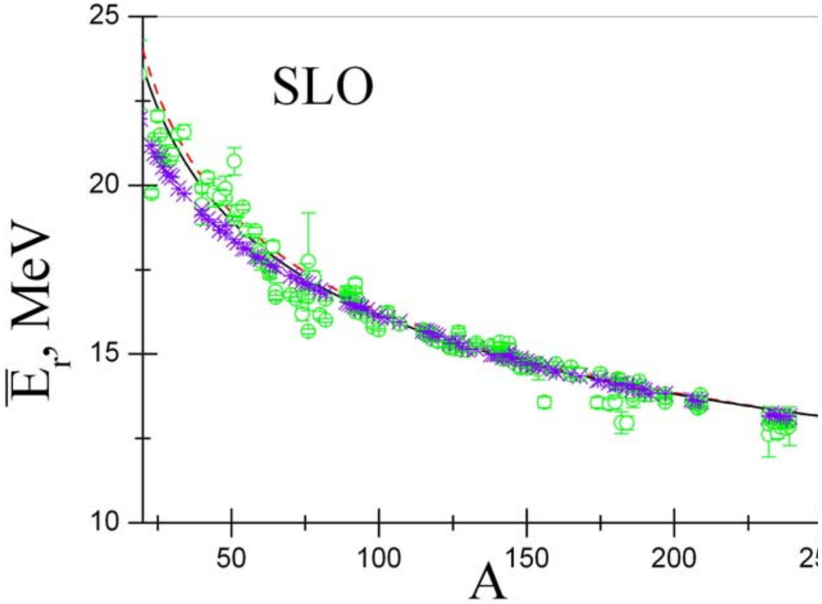
For kinetic equation description of nuclear dynamics, energy-dependent component arises from memory-dependent collision integral

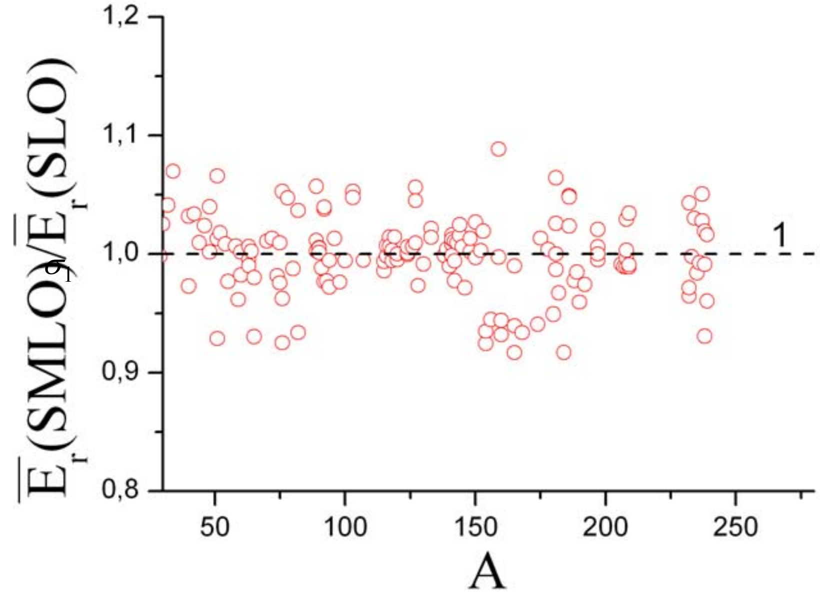
$$J(\vec{p},\vec{r},t) = \int_{-\infty}^{t} dt' R\left(t-t'\right)\delta n\left(\vec{r},\vec{p},t'\right) => -\frac{\delta n\left(\vec{r},\vec{p},\omega\right)}{\tau_c(\omega,T)} => \Gamma\left(E_\gamma = \hbar\omega, T\right)$$

GDR parameters with uncertainties from renewed database

GDR energies

$$\bar{E}_r = \frac{E_1\sigma_1 + E_2\sigma_2}{\sigma_1+\sigma_2} = \begin{cases} (E_1+2E_2)/3; \ \beta_2 > 0 \ (\sigma_2 = 2\sigma_1) \\ (2E_1+E_2)/3; \ \beta_2 < 0 \ (\sigma_2 = \sigma_1/2) \end{cases}$$





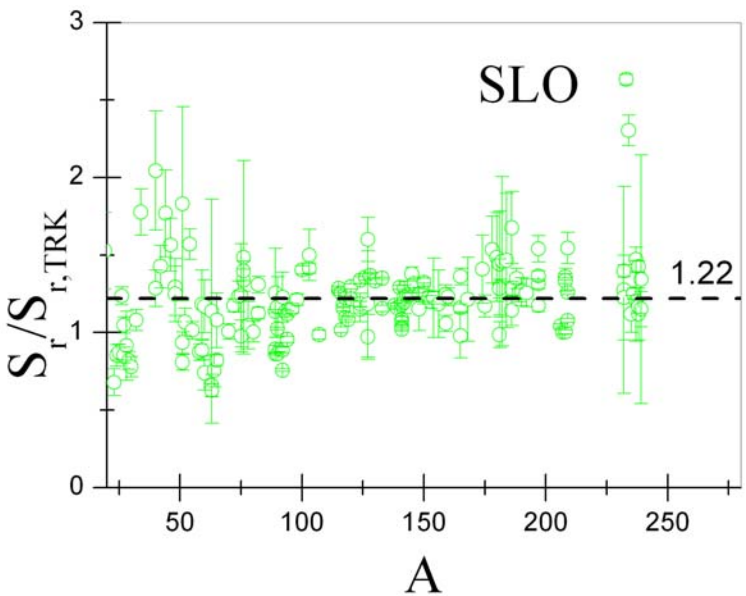
Systematic for renewed data : —— $\bar{E}_r = 31.2/A^{1/3} + 20.6/A^{1/6} \ (MeV)$

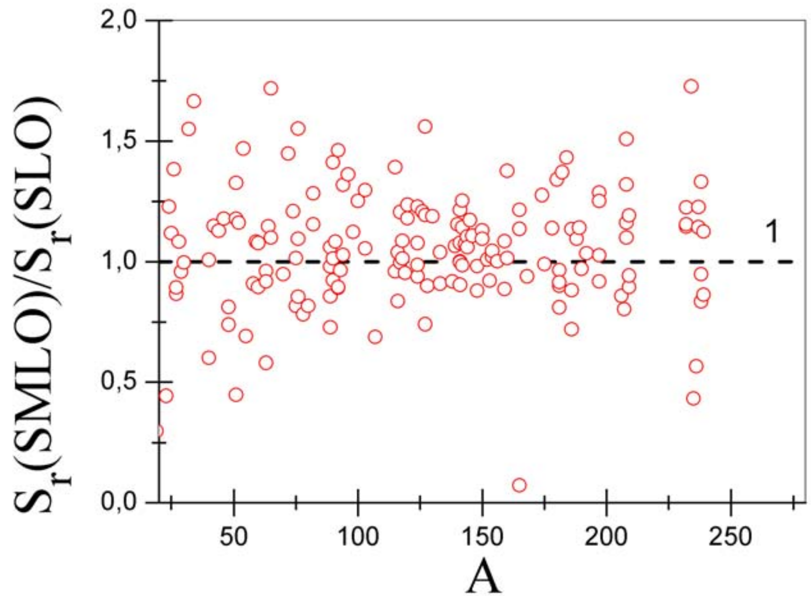
X – $\bar{E}_r = 4.755(1+108.0I^2)/A^{1/3} + 32.788(1-7.5899I^2)/A^{1/6} \ (MeV); I=(N-Z)/A$

\- - - - S.S. Dietrich, B.L. Berman(1988), $\bar{E}_r = 27.47/A^{1/3} + 22.06/A^{1/6} \ (MeV)$

O – new values

Energy weighted sum rule for isovector E1 transitions





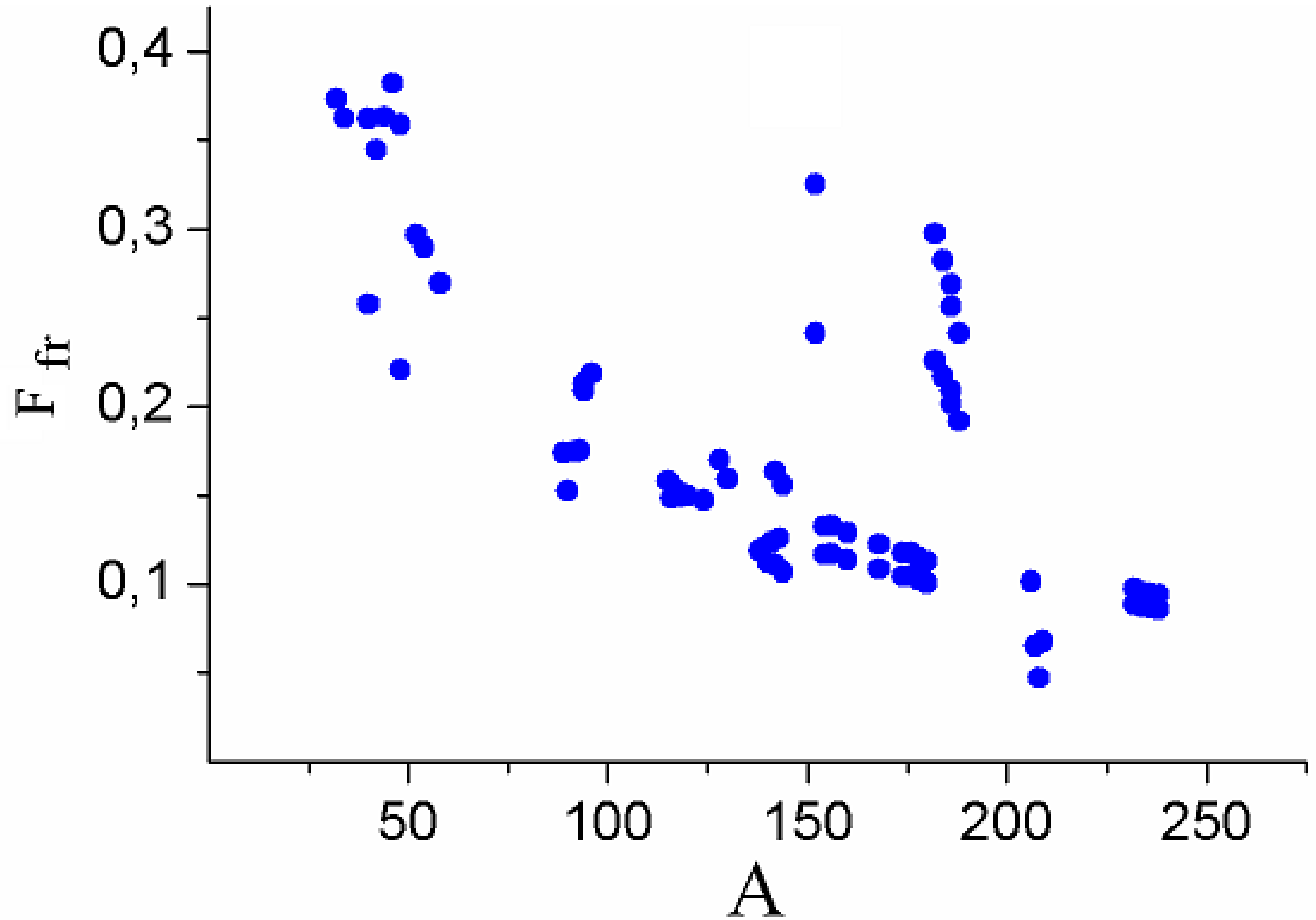
$$S_{EWSR} \equiv m_1 = \text{const} \cdot S_r, \quad S_r = \int_0^\infty \sigma(E_\gamma) dE_\gamma, \quad S_r(\text{ SLO}) = \pi/2 \sum_{j=1}^{n} \sigma_{r,j} \Gamma_{r,j}$$

$$S_r(\text{SMLO}) = \int_0^{50\,MeV} \sigma(E_\gamma) dE_\gamma \qquad S_r(\text{TRK}) = 60 \cdot NZ/A \ (\text{mb} \cdot \text{MeV})$$

Mean value of enhancement factor to TRK sum rule ~ 1.22 and is not contradictory to Gell-Mann- Goldberger-Thirring (GGT) sum rule (Eisenberg&Greiner)

Contribution of the fragmentation component

$$F_{fr} = (\Gamma_{r,j} - \Gamma^{coll}_{r,j}) / \Gamma_{r,j}$$



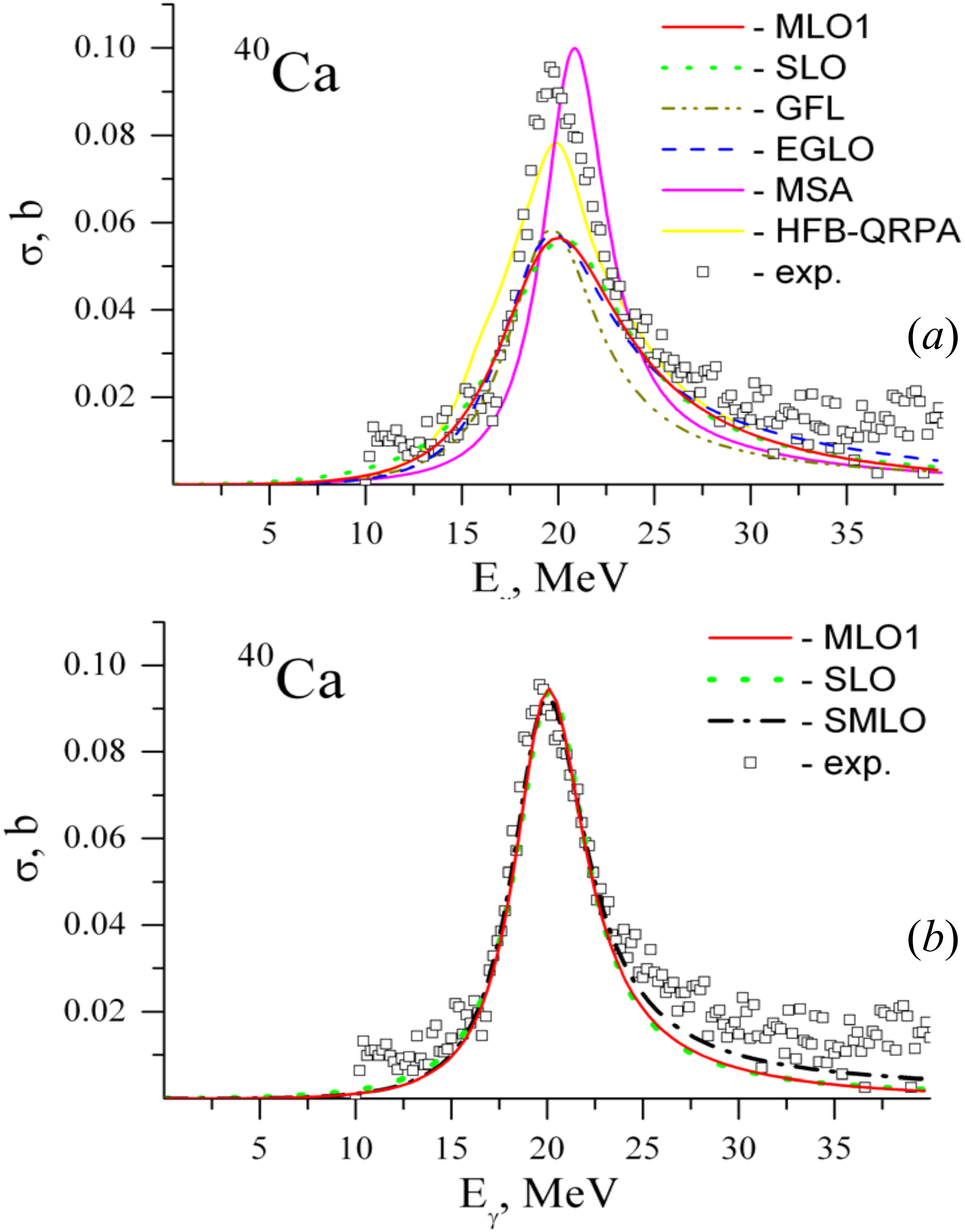
Volume(J) and surface(Q) coefficients of the symmetry energy

$$\overline{E}_r \equiv \sqrt{\frac{m_1}{m_{-1}}} = c\,J_1\,A^{-1/3}/\sqrt{1+d\cdot(J/Q)A^{-1/3}}$$

$$E_{sym} = A\cdot I^2\cdot J/(1+\frac{9J}{4Q}A^{-1/3}),\quad I=\frac{N-Z}{A}$$

$J,\ \ J/Q$	***Myers et al.*** **(c=3)**	***Lipparini et al.*** **(c=15/4)**
Used previously	36.8, 2.18	32.5, 1.00
Sph. + axial def. nuclei (MLO)	34.0, 2.03	38.8, 1.6

The photoabsorption cross sections and RSF



Comparison of the photoabsorption cross section calculated with different database for GDR parameters: (*a*) - old systematics (Berman&Fultz); (*b*) - renewed GDR parameters.

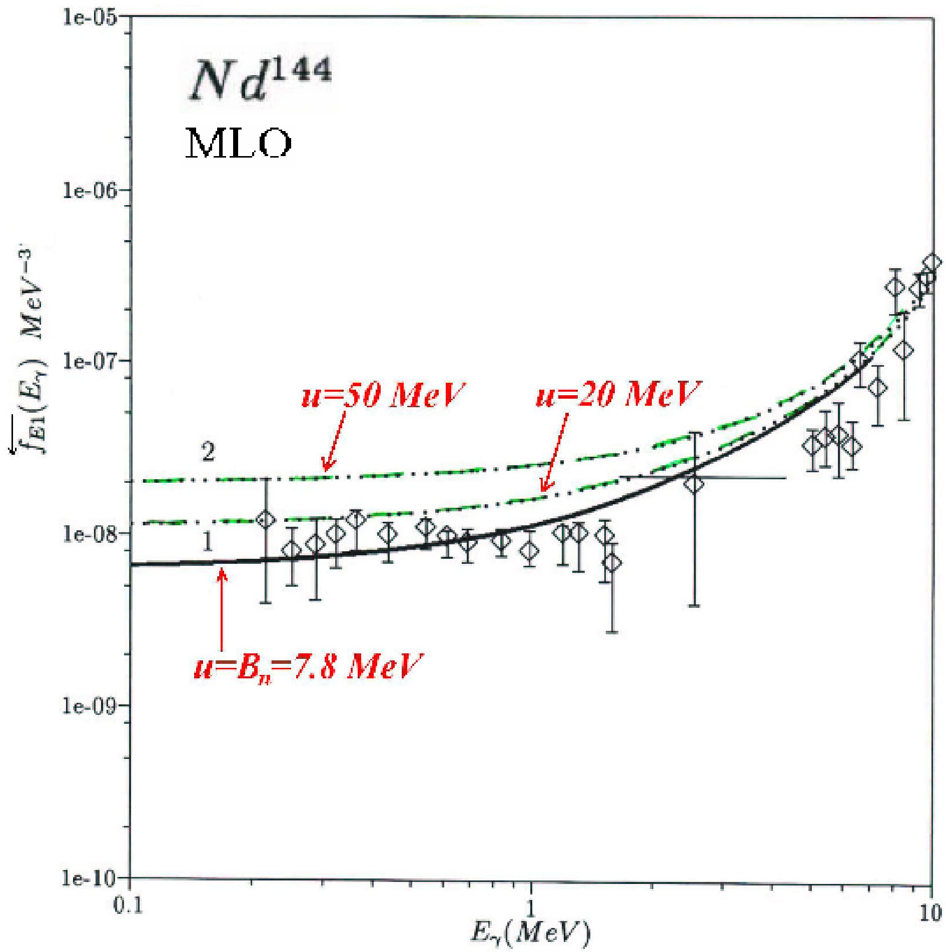
Averaged HFB-QRPA microscopic approach by S. Goriely et al NP A706 (2002) 217; A739 (2004) 331

MSA - semiclassical moving surface method by V.I. Abrosimov, O.I.Davidovskaya Izvestiya RAN. 68 (2004)200; Ukrainian Phys. Jour. 51 (2006)234

Exp.data - V.A. Erokhova et al Izvestiya RAN. Seriya Fiz. **67** (2003) 1479

Excitation energy dependence of RSF

(Brink hypothesis violation)



Low-energy part of gamma-decay RSF is enhanced for transitions at high excitation energies

$$\overleftarrow{f}\left(E_\gamma \to 0\right) \sim T_i = const$$

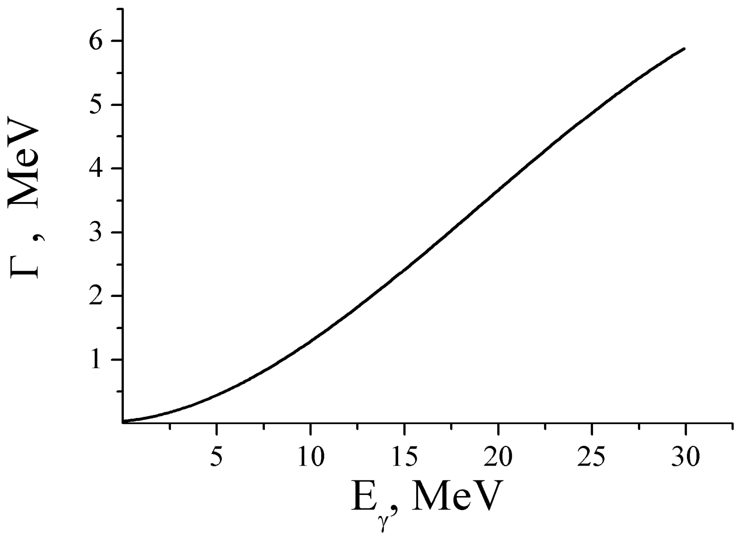
Role of folding procedure in microscopic calculations without 2p2h states

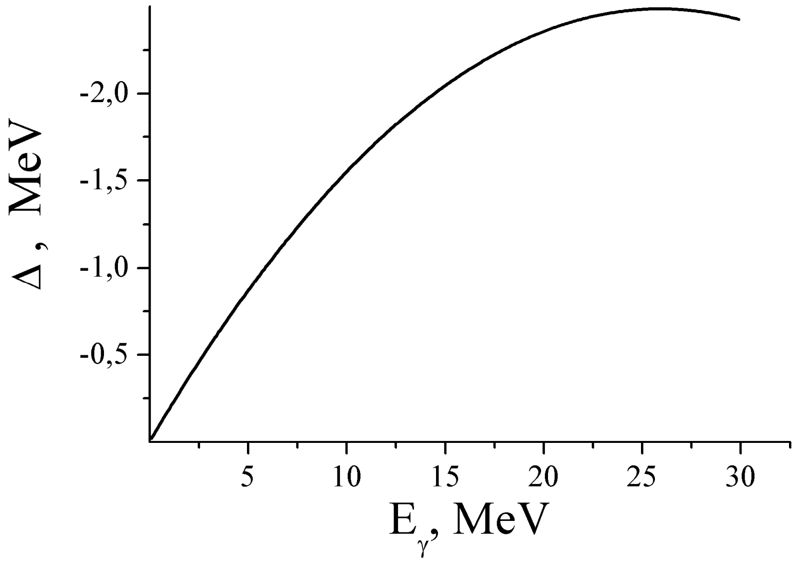
$$f_{E1}\left(E_\gamma\right) = \int_{-\infty}^{+\infty} f_L(E'_\gamma, E_\gamma) f_{E1}^{(Q)RPA}(E'_\gamma) dE'_\gamma$$

$$f_L(E'_\gamma, E_\gamma) = \frac{1}{2\pi} \frac{\Gamma(E_\gamma)}{\left(E'_\gamma - E_\gamma - \Delta(E_\gamma)\right)^2 + \Gamma^2(E_\gamma)/4}$$

R.D. Smith et al. P R**C38** (1988)100; *S.Drozdz et al*. P Rep. **197** (1990)1; *F.T.Baker et al*. P Rep. **289** (1997)235

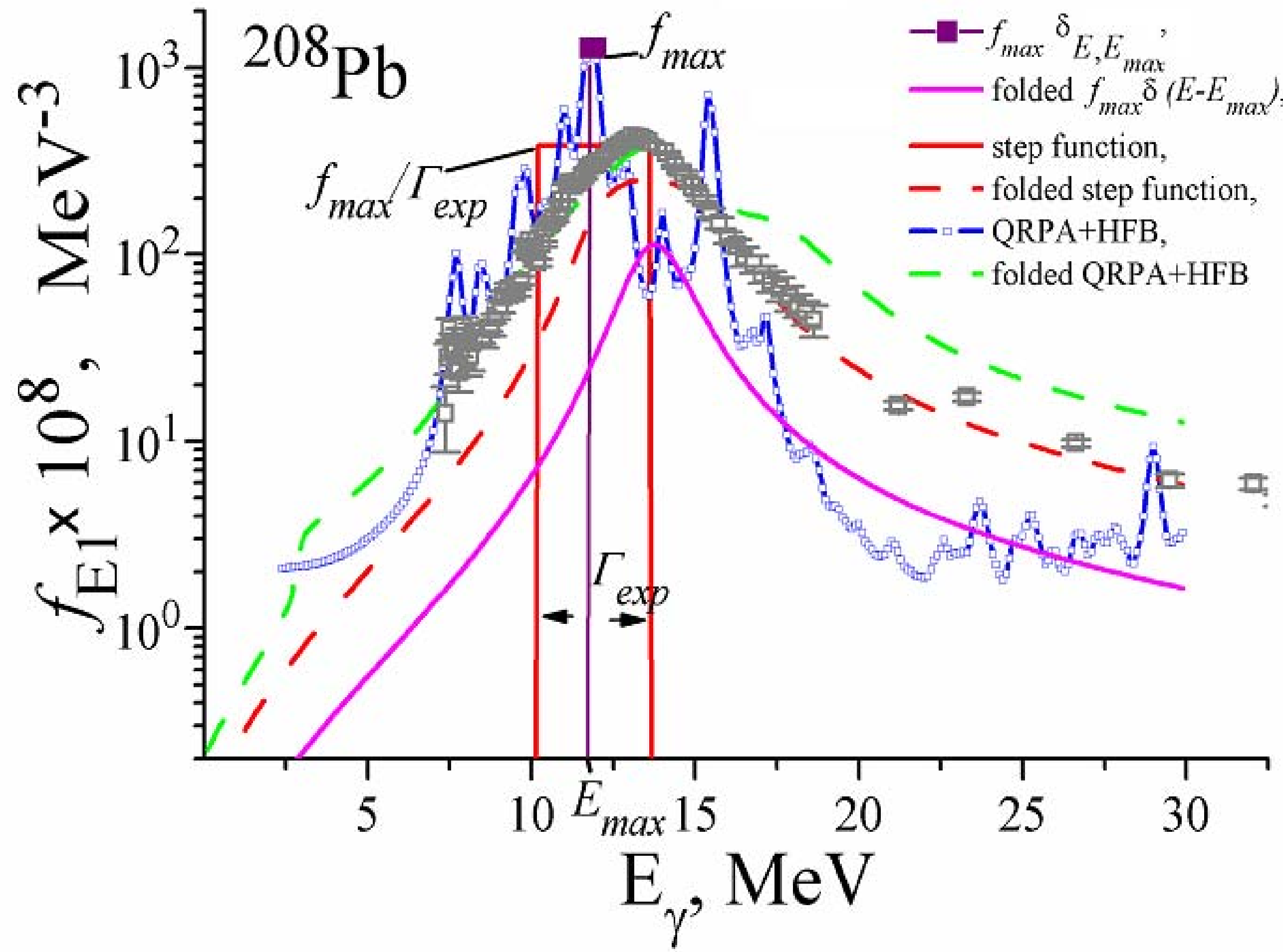
Width and energy shift for averaging HFB+QRPA results





$$\Gamma(E_\gamma) = a_0 + a_1 E_\gamma + a_2 E^2{}_\gamma + a_3 E^3{}_\gamma \qquad \Delta(E_\gamma) = b_0 + b_1 E_\gamma + b_2 E^2{}_\gamma$$

S. Goriely et al. NPA **706**, 217 (2002); **739**, 331 (2004);
S. Goriely, private communication



Calculations beyond QRPA are necessary for careful investigation of contribution of the processes on slops of the GDR peak