PHYSICAL CRITERIA OF DATA RELIABILITY AND SYSTEMATIC UNCERTAINTIES OF PHOTONEUTRON REACTION CROSS SECTIONS

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ФИЗИЧЕСКИЕ КРИТЕРИИ ДОСТОВЕРНОСТИ ДАННЫХ И СИСТЕМАТИЧЕСКИЕ ПОГРЕШНОСТИ СЕЧЕНИЙ ФОТОНЕЙТРОННЫХ РЕАКЦИЙ

LXX International Conference «NUCLEUS–2020.
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The talk continue the research of the very old and well-known problems that at the same time are a modern and very interesting

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the problems of significant disagreements between photonuclear reaction cross sections, primarily those of partial reactions, obtained in various experiments.

The majority of experimental data for total and partial photonuclear reaction cross sections was obtained at Livermore (USA) and Saclay (France)

Atlas of Photoneutron cross sections obtained with monoenergetic photons
S.S.Dietrich, B.L.Berman. Atom. Data and Nucl. Data Tables, 38 (1988) 199.

Berman's library - EXFOR entries L0001 – L0059 (about 500 data sets), databases, Atlases, Reviews.

For many nuclei (almost all stable nuclei) – cross sections of reactions

$(\gamma, 1n)$, $(\gamma, 2n)$, $(\gamma, 3n)$, $(\gamma, Sn) = (\gamma, 1n) + (\gamma, 2n) + (\gamma, 3n) + \ldots$, $(\gamma, xn) = (\gamma, 1n) + 2(\gamma, 2n) + 3(\gamma, 3n) + \ldots$

Statistic (numbers of data sets for near all stable nuclei)

Quasimonoenergetic photons				Bremsstrahlung
Livermore	Both	Saclay	Other	
~240 data sets	~100 data sets (19 nuclei)	~250 data sets	~20	Several tens

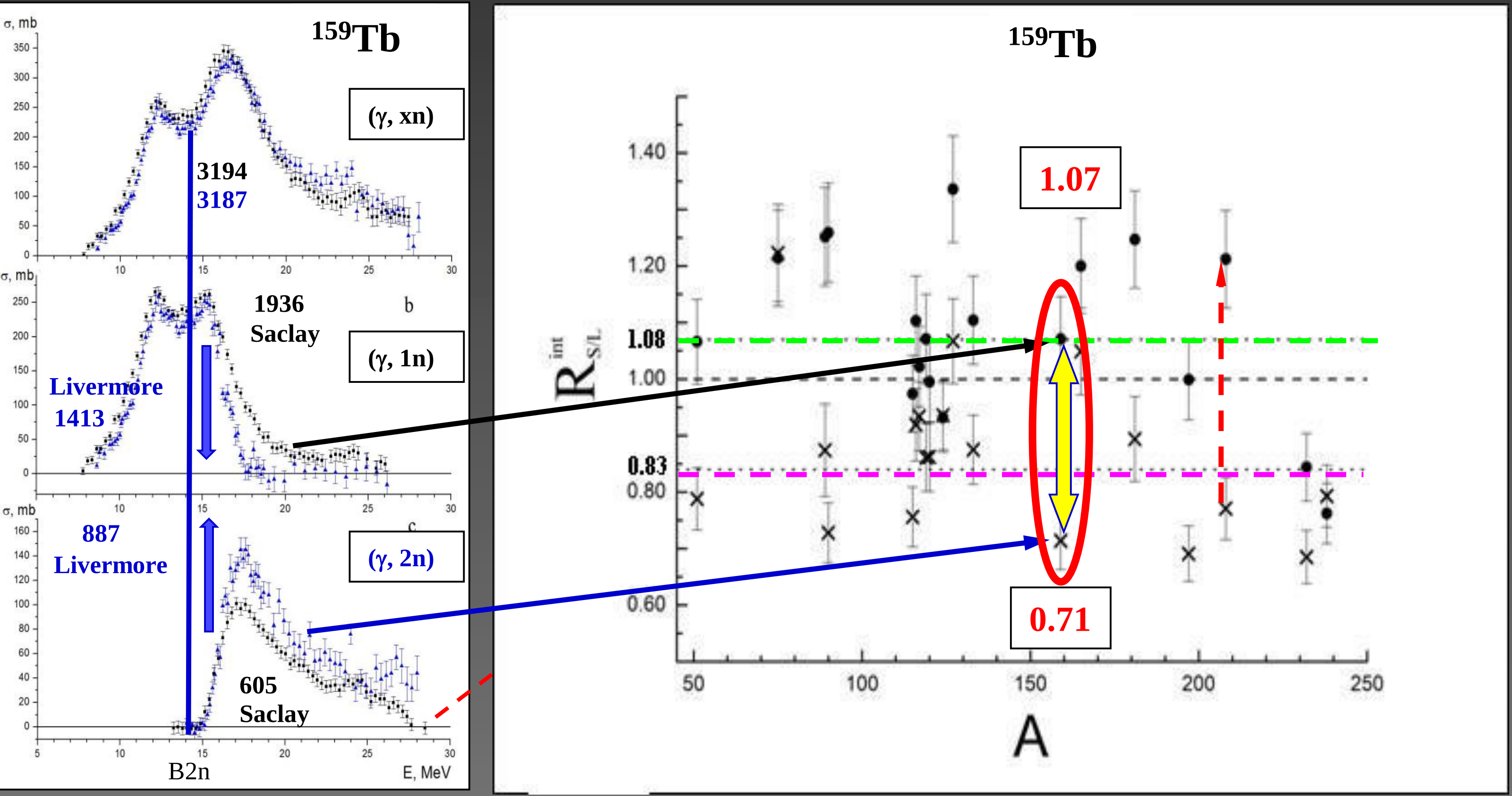
Main problem: significant disagreements

19 nuclei: ^{51}V, ^{75}As, ^{89}Y, ^{90}Zr, ^{115}In, ^{116,117,118,120,124}Sn, ^{127}I, ^{133}Cs, ^{159}Tb, ^{165}Ho, ^{181}Ta, ^{197}Au, ^{208}Pb, ^{232}Th, ^{238}U

Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности

V.V.Varlamov, N.N.Peskov, D.S.Rudenko, M.E.Stepanov. Consistent Evaluation of Photoneutron Reaction Cross Sections Using Data Obtained in Experiments with Quasimonoenergetic Annihilation Photon Beams at Livermore (USA) and Saclay (France). INDC(CCP)-440, IAEA NDS, Vienna, Austria, 2004, p. 37.

Ratios of integrated cross sections $R^{int} = \sigma^{int}_S / \sigma^{int}_L$ for 19 nuclei investigated at both Saclay and Livermore.



Circles - ratios for (γ, 1n) reactions – are larger than 1.0:

<R> ~ 1.08.

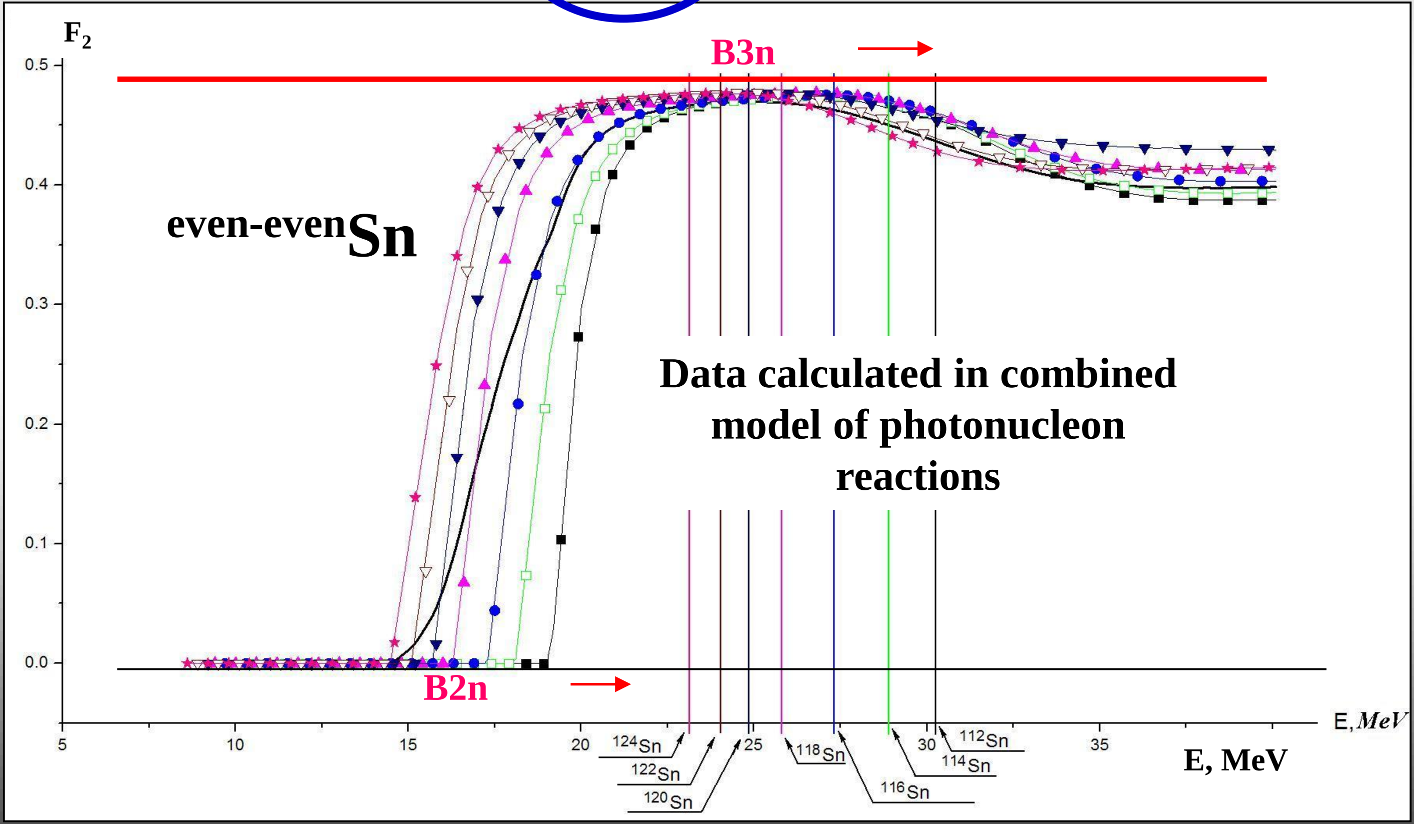
Crosses - ratios for (γ, 2n) reactions – are smaller than 1.0:

<R> ~ 0.83.

I, Ta, Pb

Main objective physical criterion for data reliability

$$F_2 = \frac{\sigma(\gamma, 2n)}{\sigma(\gamma, 1n) + 2\sigma(\gamma, 2n) + 3\sigma(\gamma, 3n) + \ldots} < 0.50\ (!)$$



Data calculated in combined model of photonucleon reactions

The natural and physically reliable energy dependence of F_2 should be following:

– Below the (γ, 2n) reaction threshold B2n only the (γ, 1n) reaction is possible: $F_2 = 0$;

– Above B2n both (γ, 1n) and (γ, 2n) reactions are possible, F_2 increases due to competition between decreasing $\sigma(\gamma, 1n)$ and increasing $\sigma(\gamma, 2n)$, going to the theoretical limit of 0.50, but never reach it because of a high–energy part in $\sigma(\gamma, 1n)$;

– Above the B3n threshold the (γ, 3n) reaction is also possible, F_2 decreases due to a $3\sigma(\gamma, 3n)$.

The natural physical additions:

– $F_1 < 1.00$,

– $F_2 < 0.50$,

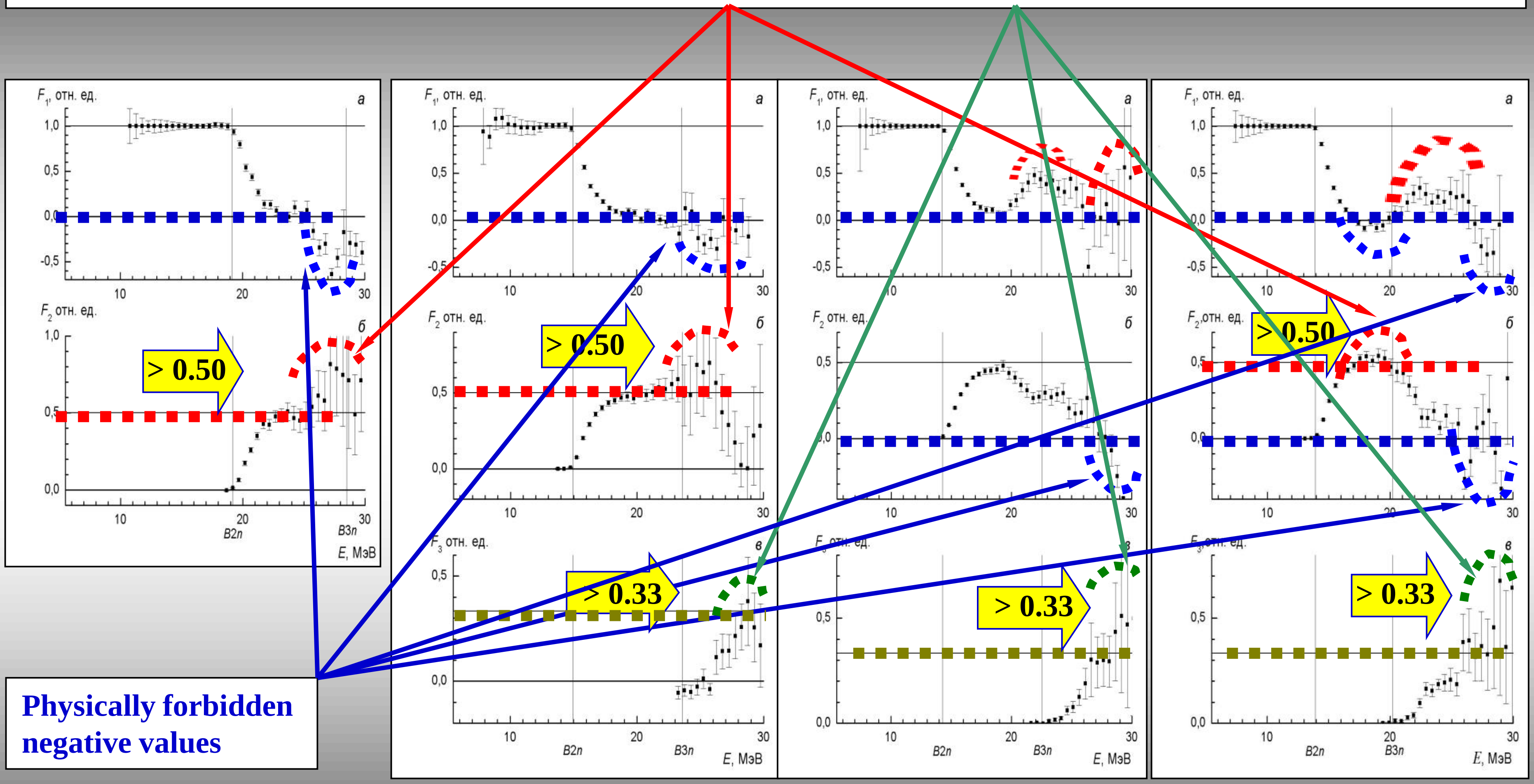
– $F_3 < 0.33$,

– $F_4 < 0.25$,

– $F_5 < 0.20$…

Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности

Physically unreliable neutron distributions between reactions with multiplicities «1» - «2», «1» - «3» and «2» - «3».



Physically forbidden negative values

^{91}Zr ^{94}Zr ^{188}Os ^{189}Os

Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности

New experimental-theoretical method of evaluation using combined model of photonuclear reactions:

- **initial data – experimental neutron yield reaction (γ, xn) cross section;**
- **sorting neutrons for multiplicity is based on theoretical model.**

Combined exciton preequilibrium model based on nuclear level densities calculated in the model of Fermi-gas and taking into account the effects of nucleus deformation and its giant dipole resonance configurational and isospin splitting.

Model is well tested for description of many total photoneutron reaction cross sections for medium and heavy nuclei.

B.S.Ishkhanov, V. N. Orlin, ЭЧАЯ, 38, 460 (2007) [Phys. Part. Nucl. 39, 232 (2007)]

B.S.Ishkhanov, V. N. Orlin, ЯФ, 71, 517 (2008) [Phys. Atom. Nucl. 71, 493 (2008)]

Theoretically calculated transitional multiplicity functions $F_i^{theor} = \sigma^{theor}(\gamma, in)/\sigma^{theor}(\gamma, xn)$ are used for cross section evaluation by following way

$$\sigma^{eval}(\gamma, in) = F_i^{theor}(\gamma, in) \bullet \sigma^{exp}(\gamma, xn).$$

This approach means:

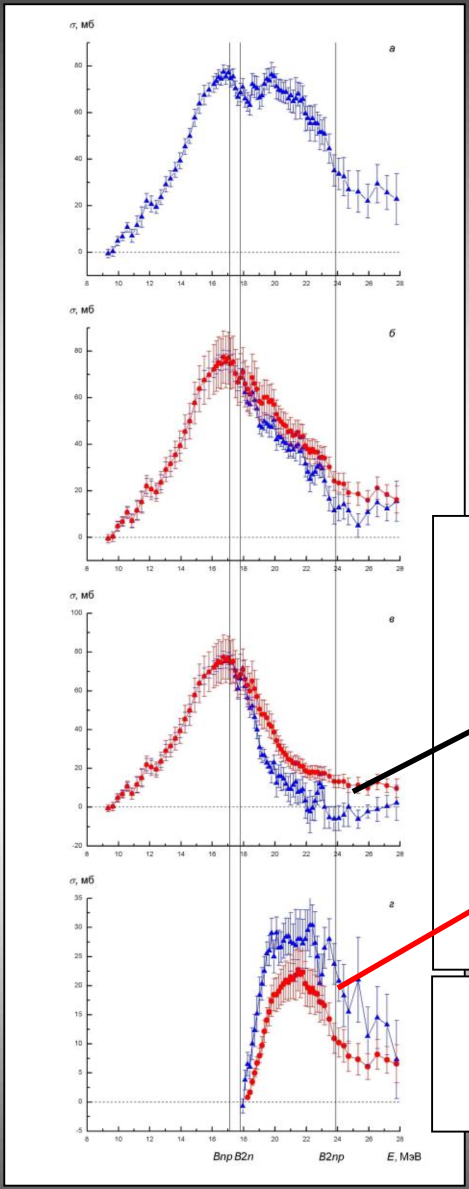
i) **the competition of partial reactions (γ, 1n), (γ, 2n) and (γ, 3n) is in accordance with equations of model;**

ii) **the sum of evaluated partial reaction cross sections**

$$\sigma^{eval}(\gamma, xn) = \sigma^{eval}(\gamma, 1n) + 2\sigma^{eval}(\gamma, 2n) + 3\sigma^{eval}(\gamma, 3n) + \dots$$

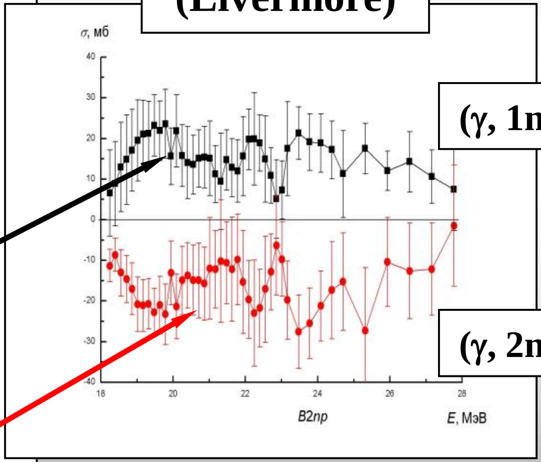
is equal to the experimental $\sigma^{exp}(\gamma, xn)$.

Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности

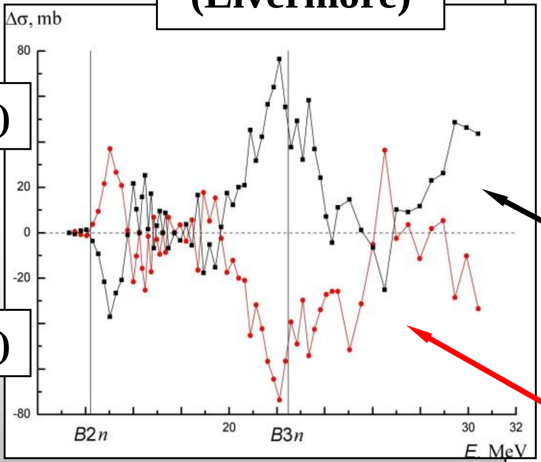


It was found that for many nuclei (^{51}V, ^{63,65}Cu, ^{75}As, ^{76,78,80,82}Se, ^{89}Y, ^{90,91,92,94}Zr, ^{103}Rh, ^{116,117,118,119,120,124}Sn, ^{115}In, ^{127}I, ^{129}Xe, ^{133}Cs, ^{138}Ba, ^{139}La, ^{140,142}Ce, ^{141}Pr, ^{145,148}Nd, ^{153}Eu, ^{159}Tb, ^{160}Gd, ^{165}Ho, ^{181}Ta, ^{186}W, ^{186,188,189,190,192}Os, ^{197}Au, ^{208}Pb, ^{209}Bi, and some others) evaluated and experimental data are significantly different.

^{65}Cu (Livermore)

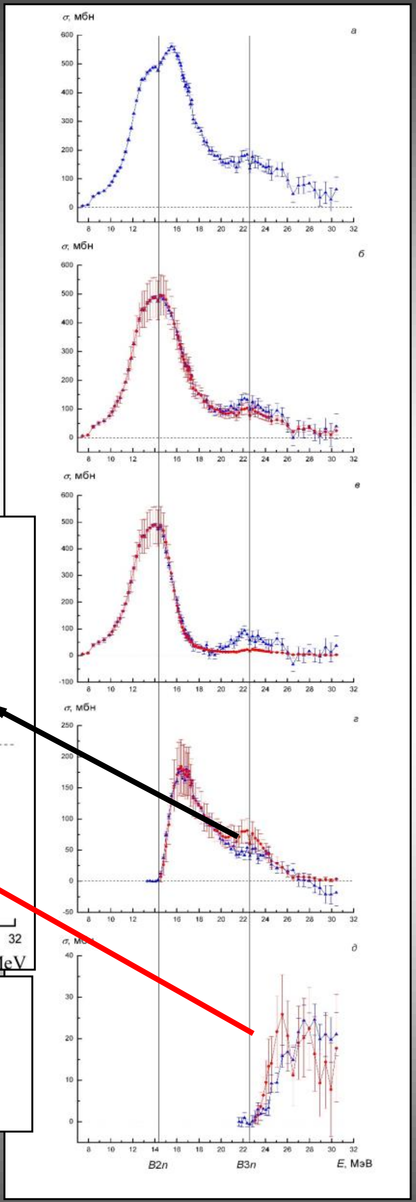


^{188}Os (Livermore)



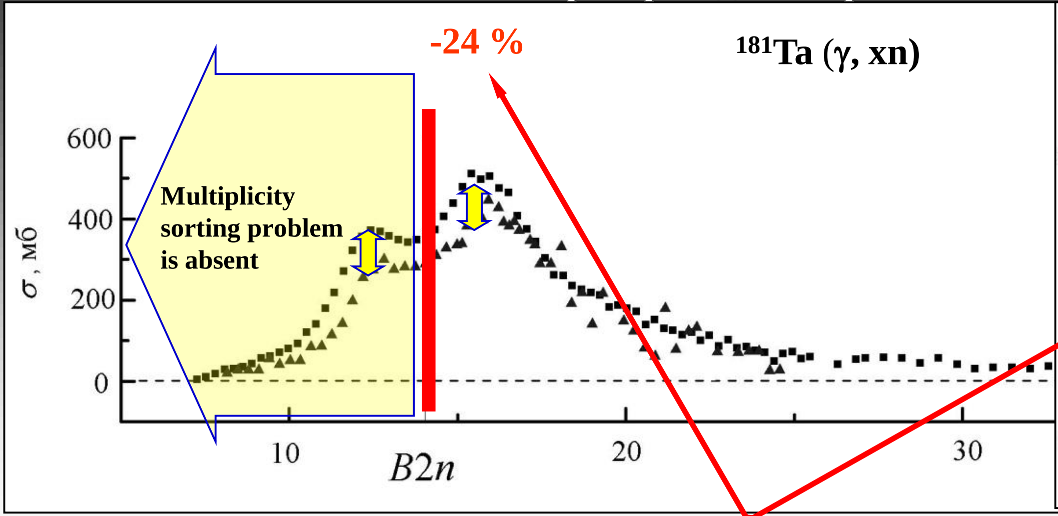
(γ, 1n)

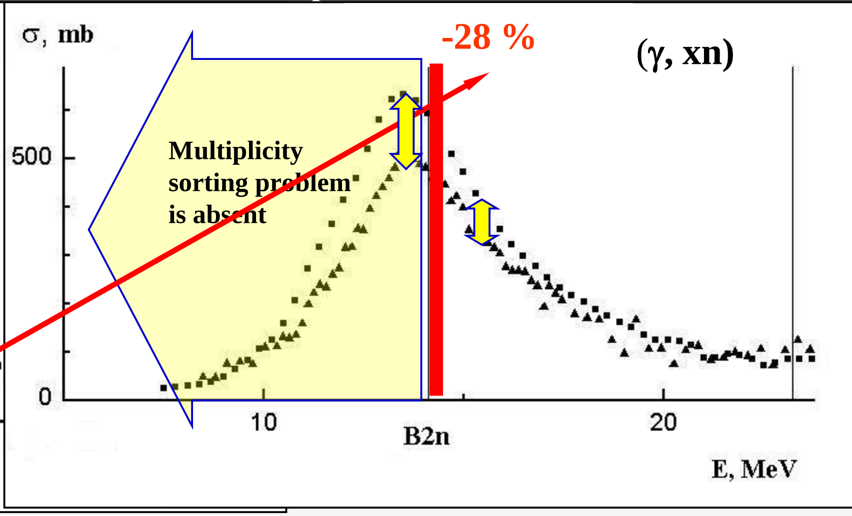
(γ, 2n)

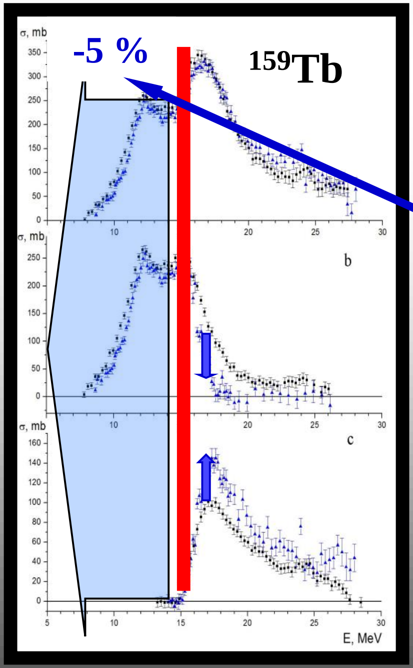


The main reason of disagreements is unreliable (erroneous) sorting of neutrons using its measured energy – spectra of neutrons are near.

Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности

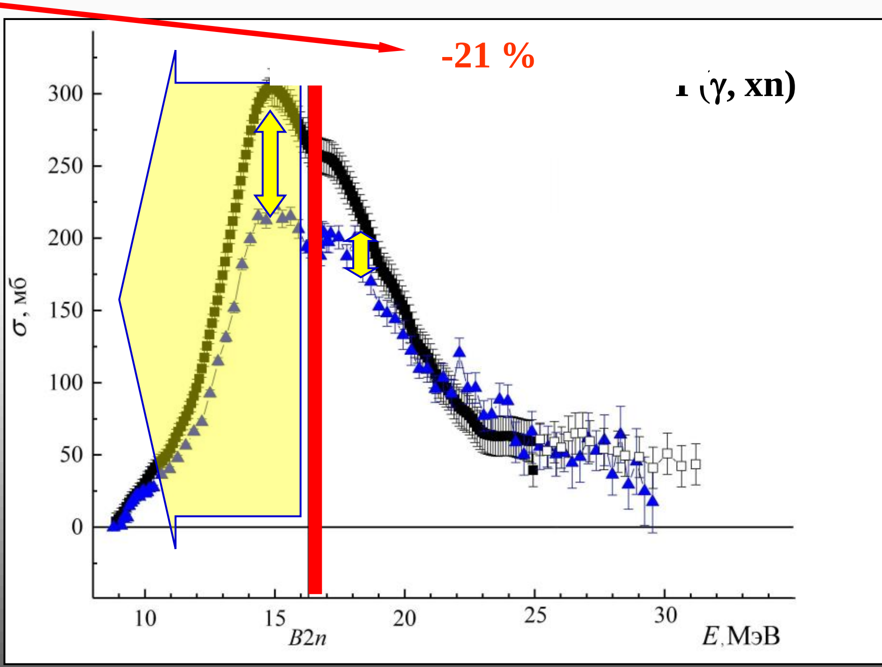




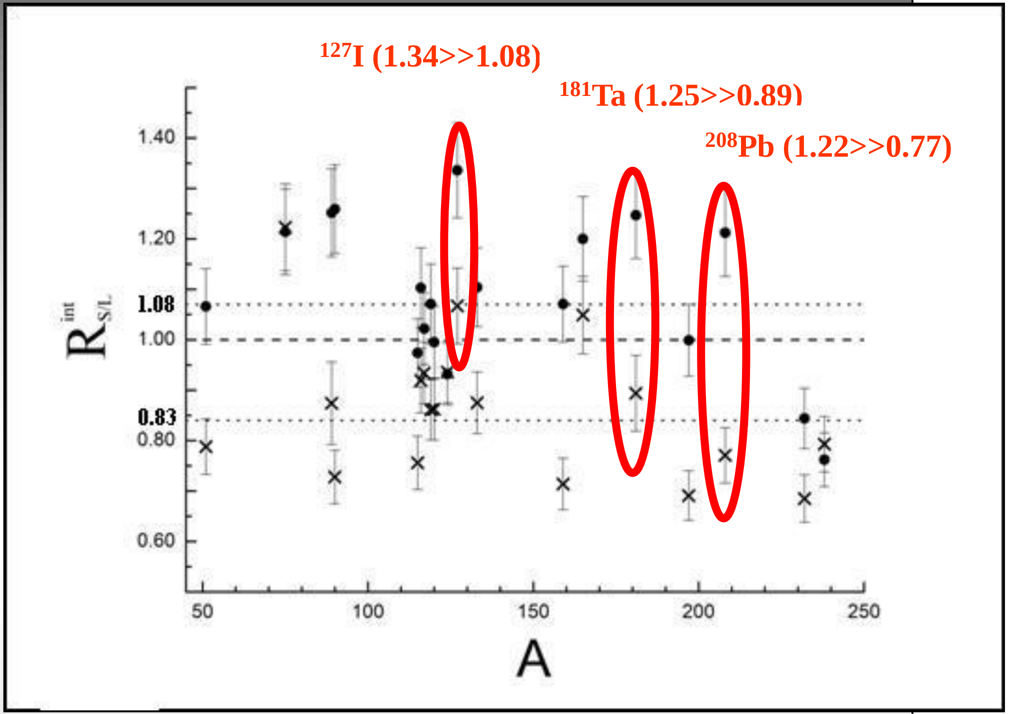


Unlike to the case of ^{159}Tb:

significant disagreements at energies $E_\gamma <$ B2n, at higher energies disagreements are smaller.



Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности



^{127}I (1.34>>1.08)

^{181}Ta (1.25>>0.89)

^{208}Pb (1.22>>0.77)

Experimental data for ^{127}I, ^{181}Ta, and ^{208}Pb are very similar: cross sections of the reactions

(γ,1n),

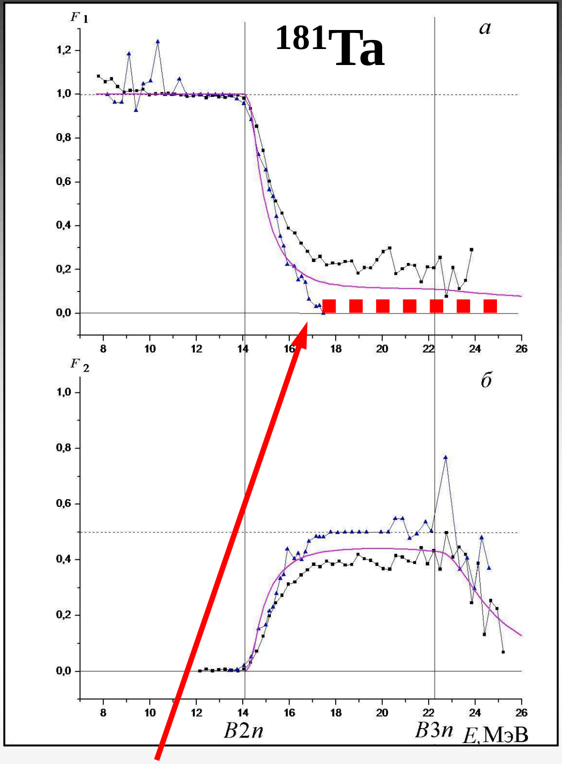
(γ,Sn) = (γ,1n)+(γ,2n)+(γ,3n) + ...,

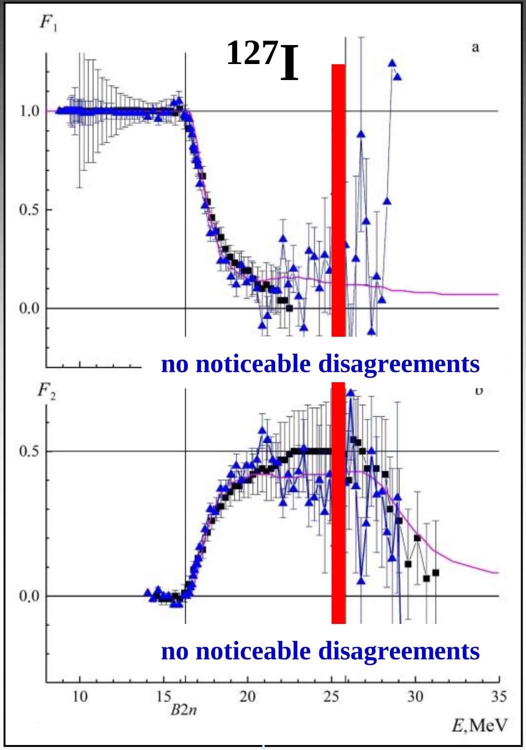
and

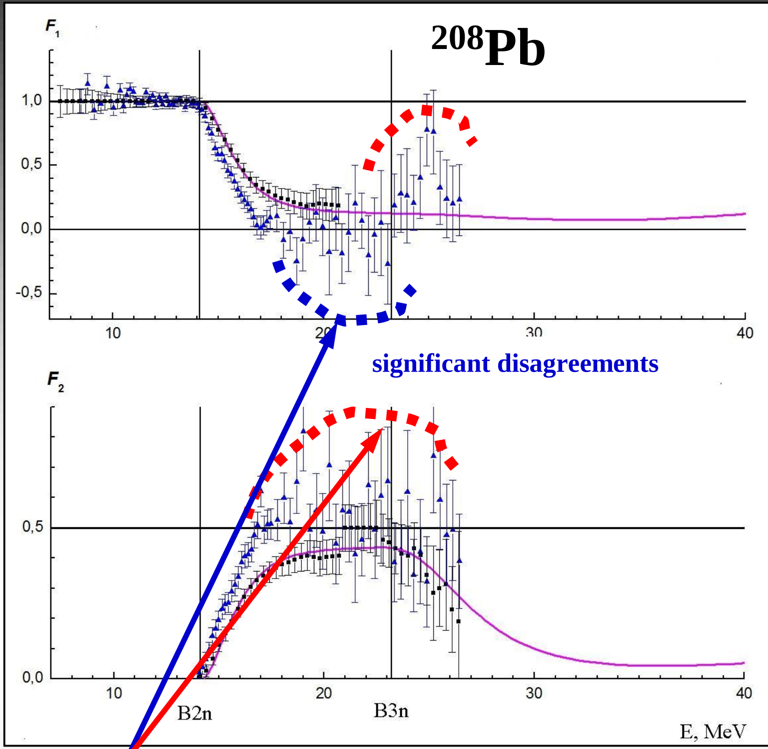
(γ,xn) = (γ,1n)+2(γ,2n)+3(γ,3n) + ...,

obtained at Saclay and Livermore are significantly different at energies below the threshold B2n of (γ,2n) reaction, where one has no the neutron multiplicity sorting problem, only neutrons from the reaction (γ,1n) exist and cross sections of all 3 reactions mentioned must be identical.

Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности







It is very important to point out that no neutrons from (γ, 1n) reaction were detected.

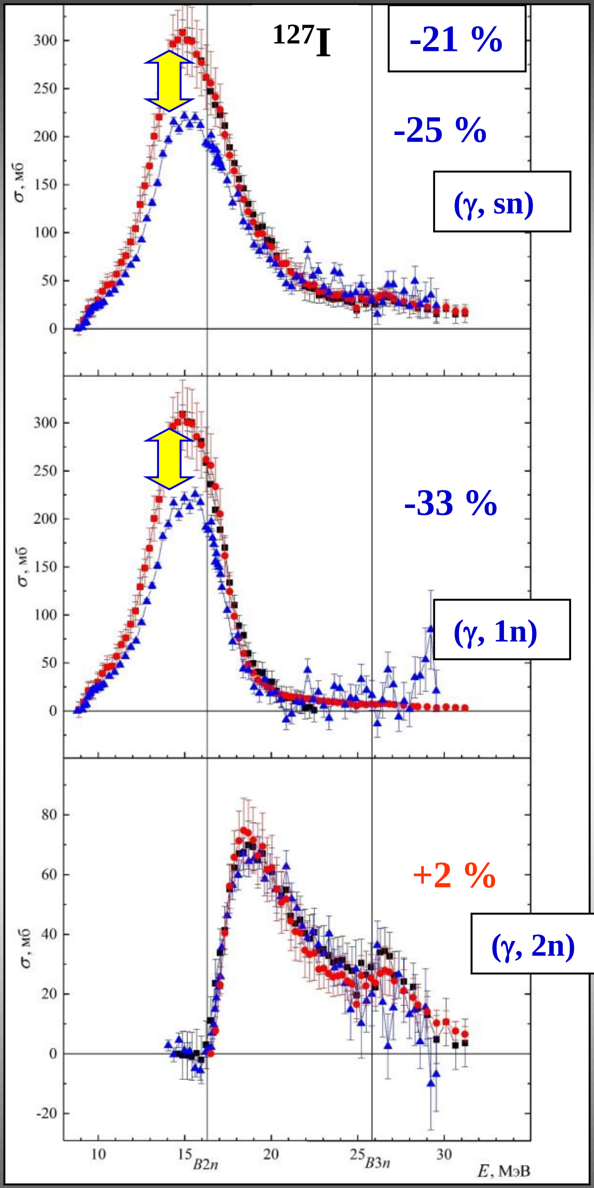
1) physically unreliable negative F_1 values;
2) physically unreliable F_2 values > 0.50.

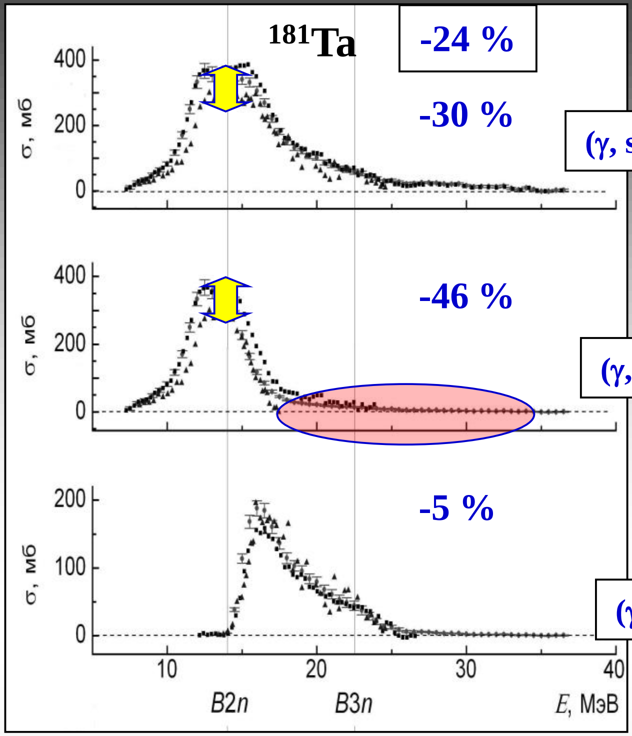
$$F_2 = \sigma(\gamma, 2n)/\sigma(\gamma, xn) = \frac{\sigma(\gamma, 2n)}{\sigma(\gamma, 1n) + 2\sigma(\gamma, 2n) + 3\sigma(\gamma, 3n) + \ldots} < 0.50$$

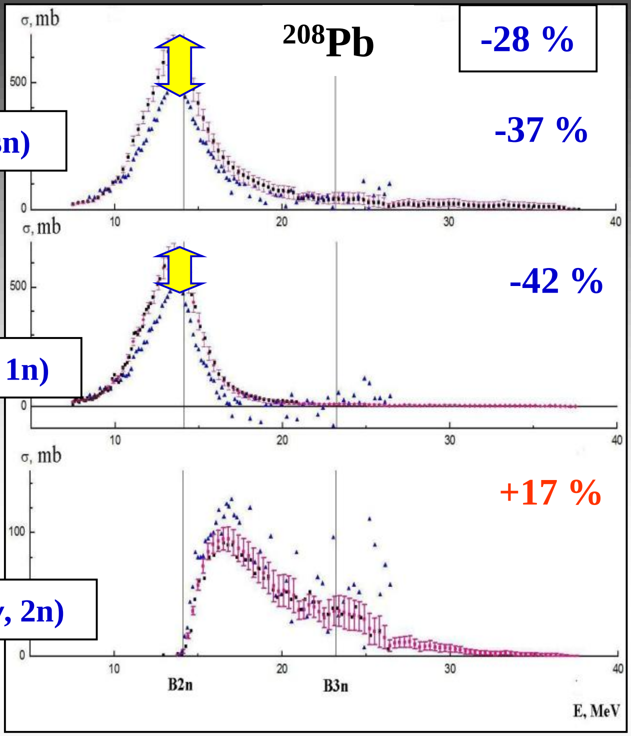
Reliability of data is doubtful.

Many data must be analyzed and evaluated!

Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности







$$\sigma^{int}_{eval}/\sigma^{int}_{L}$$

Disagreements between evaluated and experimental (γ, 1n) cross sections are noticeably larger for reaction in comparison with those for (γ, xn) reaction.

At the same time the disagreements for (γ, 2n) cross sections are significantly smaller.

⇕ **Eval – exp.**

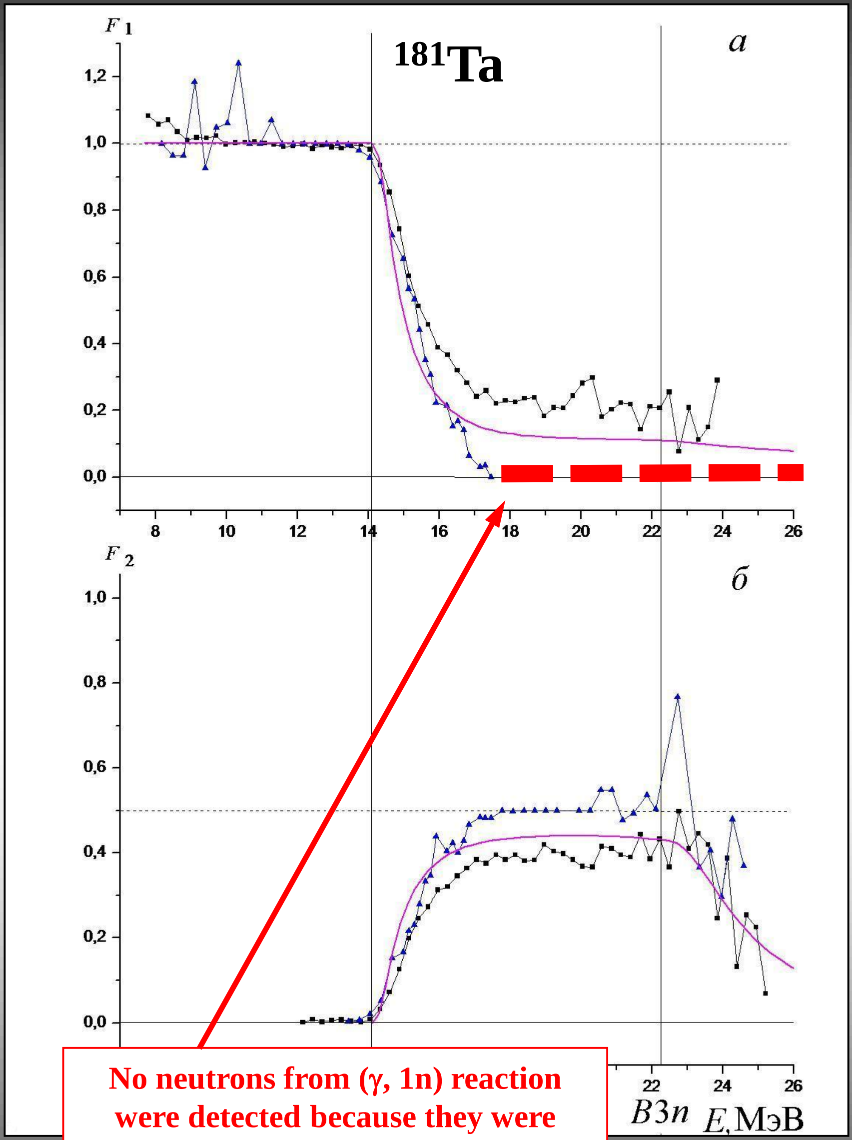
Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности

	$\sigma^{int}_{eval}/\sigma^{int}_{L}$		
Nucleus Reaction	^{127}I	^{181}Ta	^{208}Pb
(γ, xn)	1.20	1.24	1.28
(γ, sn)	1.25	1.30	1.37
(γ, 1n)	1.33	1.46	1.42
(γ, 2n)	0.98	1.05	0.83

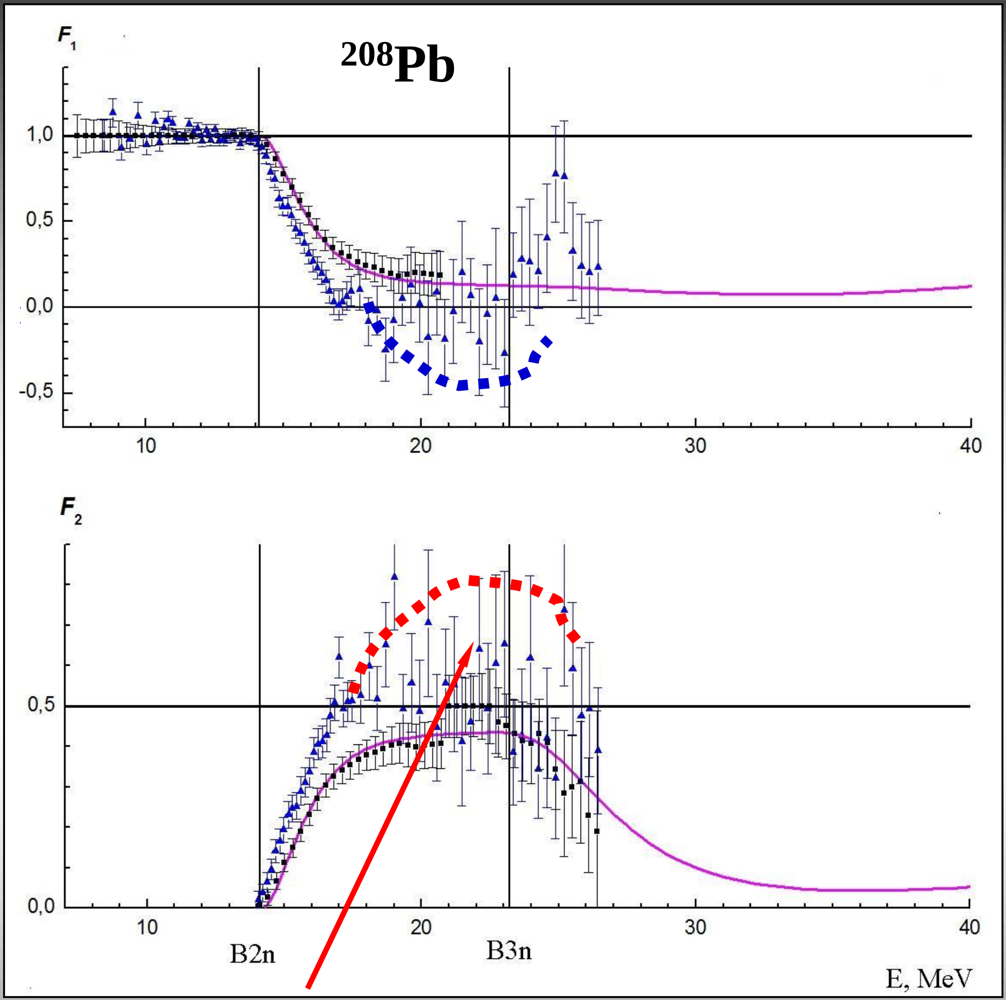
	$\sigma^{int}_{eval}/\sigma^{int}_{S}$		
Nucleus Reaction	^{127}I	^{181}Ta	^{208}Pb
(γ, xn)	0.99	1.00	1.00
(γ, sn)	1.00	0.96	1.02
(γ, 1n)	1.01	0.88	0.96
(γ, 2n)	0.94	1.16	1.16

The ratios $\sigma^{int}_{eval}/\sigma^{int}_{L}$ for (γ, 2n) reaction for ^{127}I and ^{181}Ta are very small (2 and 5 %), but for (γ, 1n) reaction are very large (33 and 46 %). It means that namely the very large underestimation of the cross-section for reaction (γ, 1n) is responsible for a substantial (by 20 and 24%) underestimations of the cross-section for the reaction (γ, xn). One is forced to conclude that in Livermore experiments many neutrons from (γ, 1n) reaction were lost. This could be resulted from some problem of neutron detection efficiency at different neutron energies.

Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности

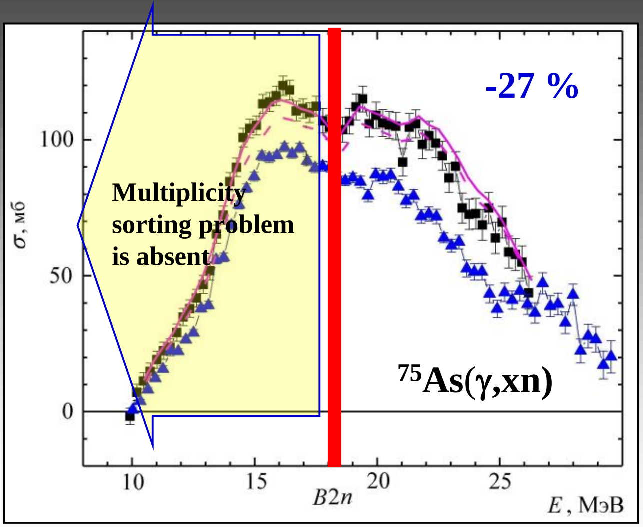


No neutrons from (γ, 1n) reaction were detected because they were lost.



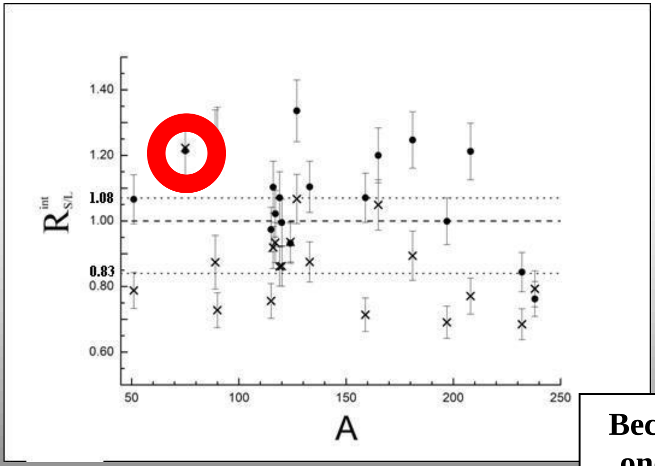
Very large F2 > 0.50 values and noticeably overestimated experimental (γ, 2n) reaction cross-section mean that many neutrons from (γ, 1n) reaction were not only lost but erroneously transported into (γ, 2n) reaction.

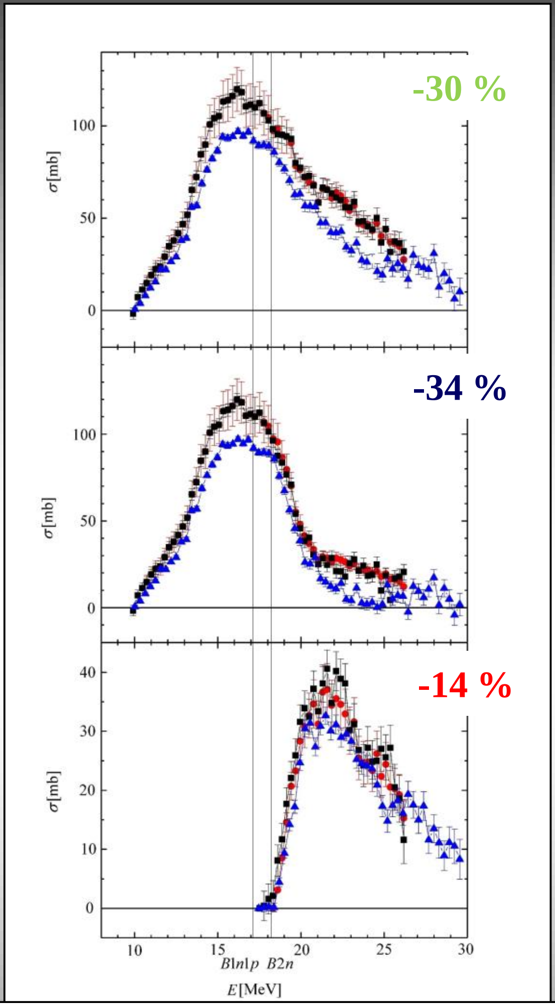
Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности



Multiplicity sorting problem is absent

1.21 ≈ 1.22





^{75}As

Reaction	$\sigma^{int}_{eval}/\sigma^{int}_{S}$	$\sigma^{int}_{eval}/\sigma^{int}_{L}$
(γ, xn)	0.99	1.27
(γ, sn)	1.00	1.30
(γ, 1n)	1.02	1.34
(γ, 2n)	0.92	1.14

The competition between partial reactions for ^{75}As is similar to those for ^{127}I and ^{181}Ta.

The only difference is large $\sigma^{int}_{eval}/\sigma^{int}_{L}$ for (γ, 2n): 14% instead of 2%, 5%.

Because in the case of ^{75}As(γ, 2n) reaction cross-section is noticeably (-14%) underestimated, one is forced to conclude that at Livermore many neutrons were lost in both (γ, 1n) and (γ, 2n) reactions.

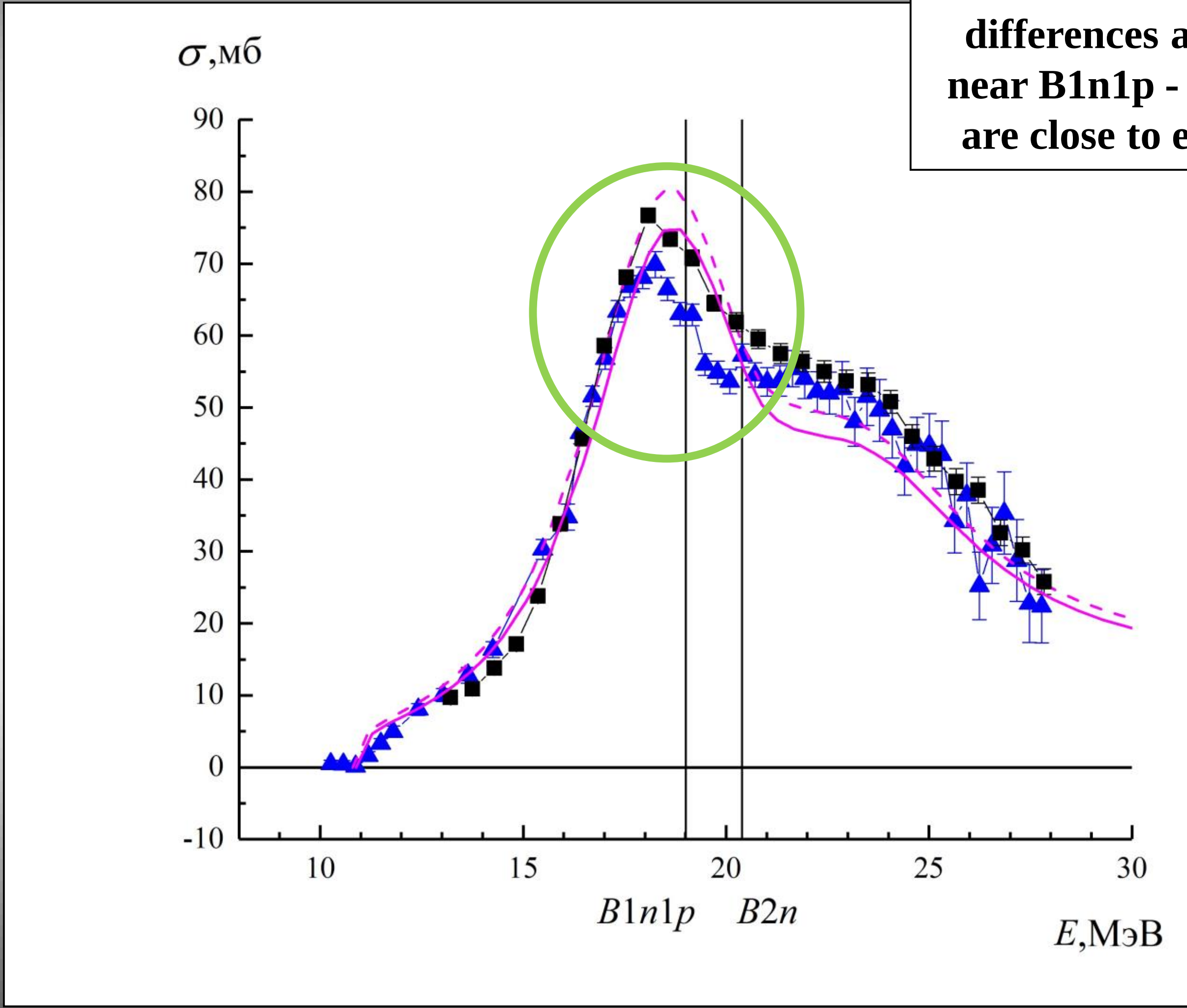
The reasons could be some technical problems of neutron detector, primarily BF3 counters.

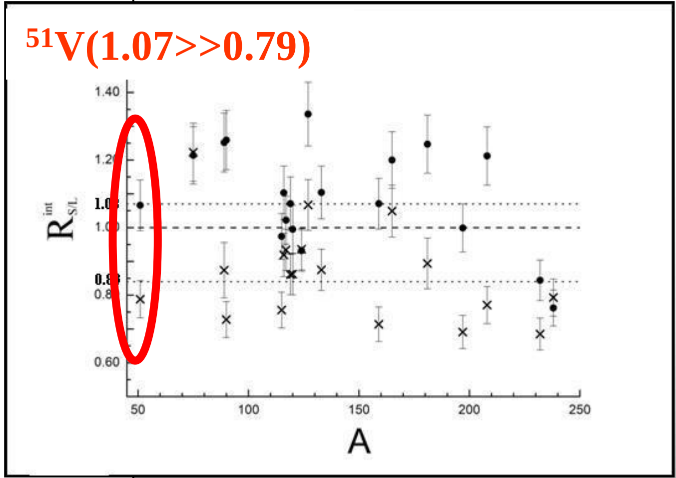
^{51}V (γ, 1n1p)

Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности

^{51}V

There are noticeable differences at energies near B1n1p - B2n which are close to each other.



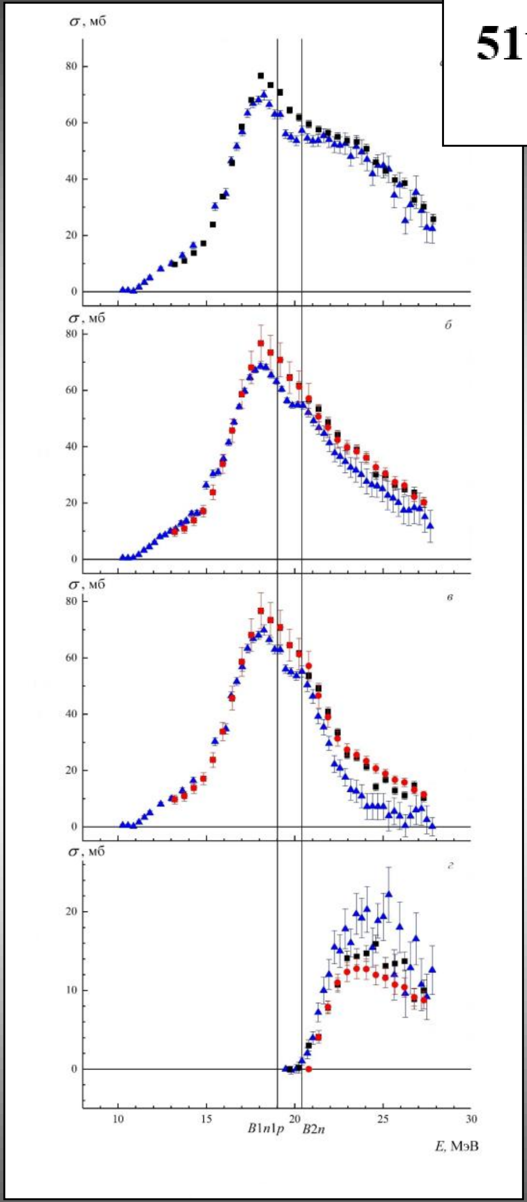

^{51}V(1.07>>0.79)

Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности

All cross sections obtained in both Livermore and Saclay experiments for reaction (γ, 1n) in fact are the sums σ(γ, 1n)+σ(γ, 1n1p). But for relatively light nuclei the (γ, 1n1p) reaction could be an important source of the systematic uncertainties of the detected neutron multiplicity determination procedure.

The source of ambiguity in the cases of relatively light nuclei is the sharing of nuclear excitation energy between neutron and proton can be similar to that for two neutrons in the reaction (γ, 2n) but the multiplicity of outgoing neutron in the reaction (γ, 1n1p) is 1 but that of both outgoing neutrons in the reaction (γ, 2n) is 2.

Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности

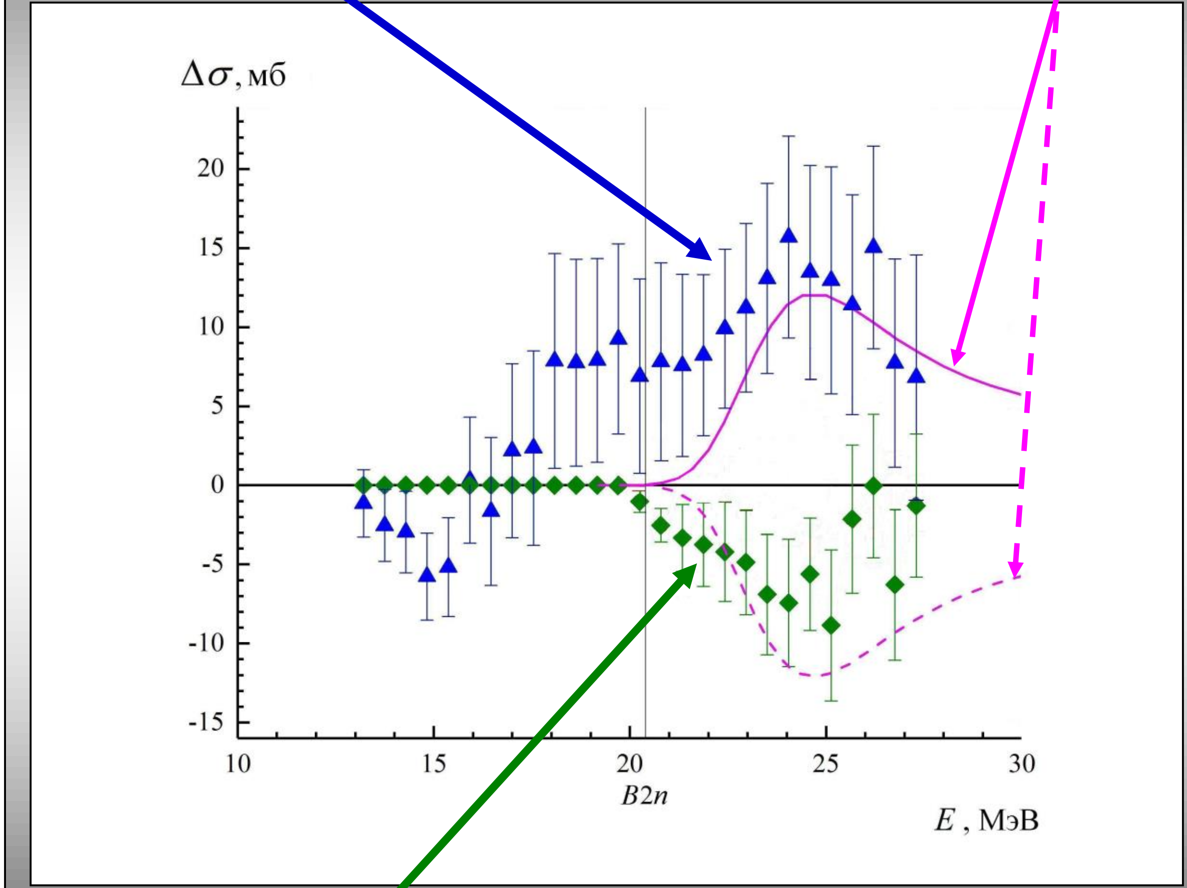


^{51}V

$$\Delta\sigma = \sigma^{eval} - \sigma^{exp}$$

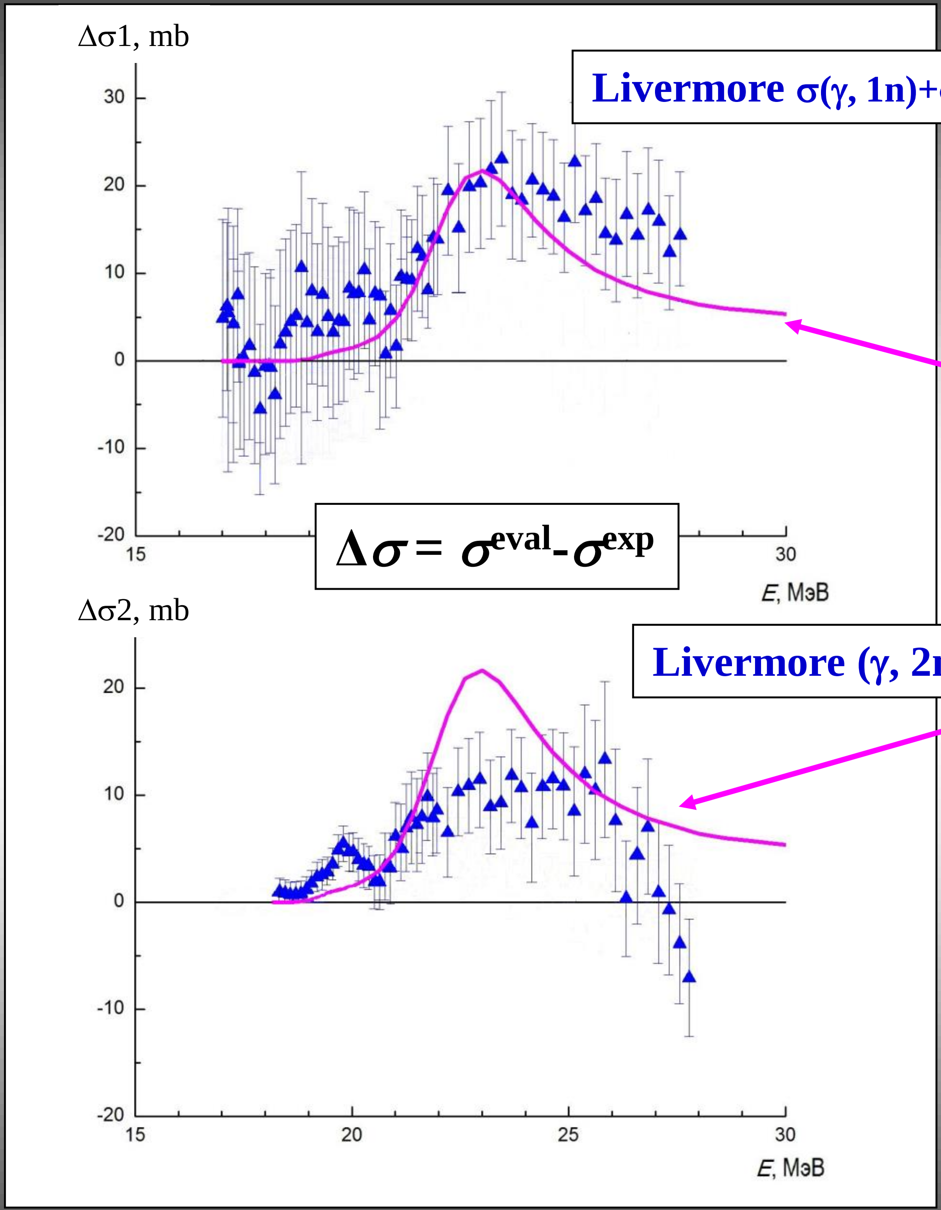
Livermore σ(γ, 1n)+σ(γ, 1n1p)

σ^{theor}(γ, 1n1p) from CMPNR



Livermore (γ, 2n)

Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности



Livermore σ(γ, 1n)+σ(γ, 1n1p)

$$\Delta\sigma = \sigma^{eval} - \sigma^{exp}$$

Livermore (γ, 2n)

^{59}Co

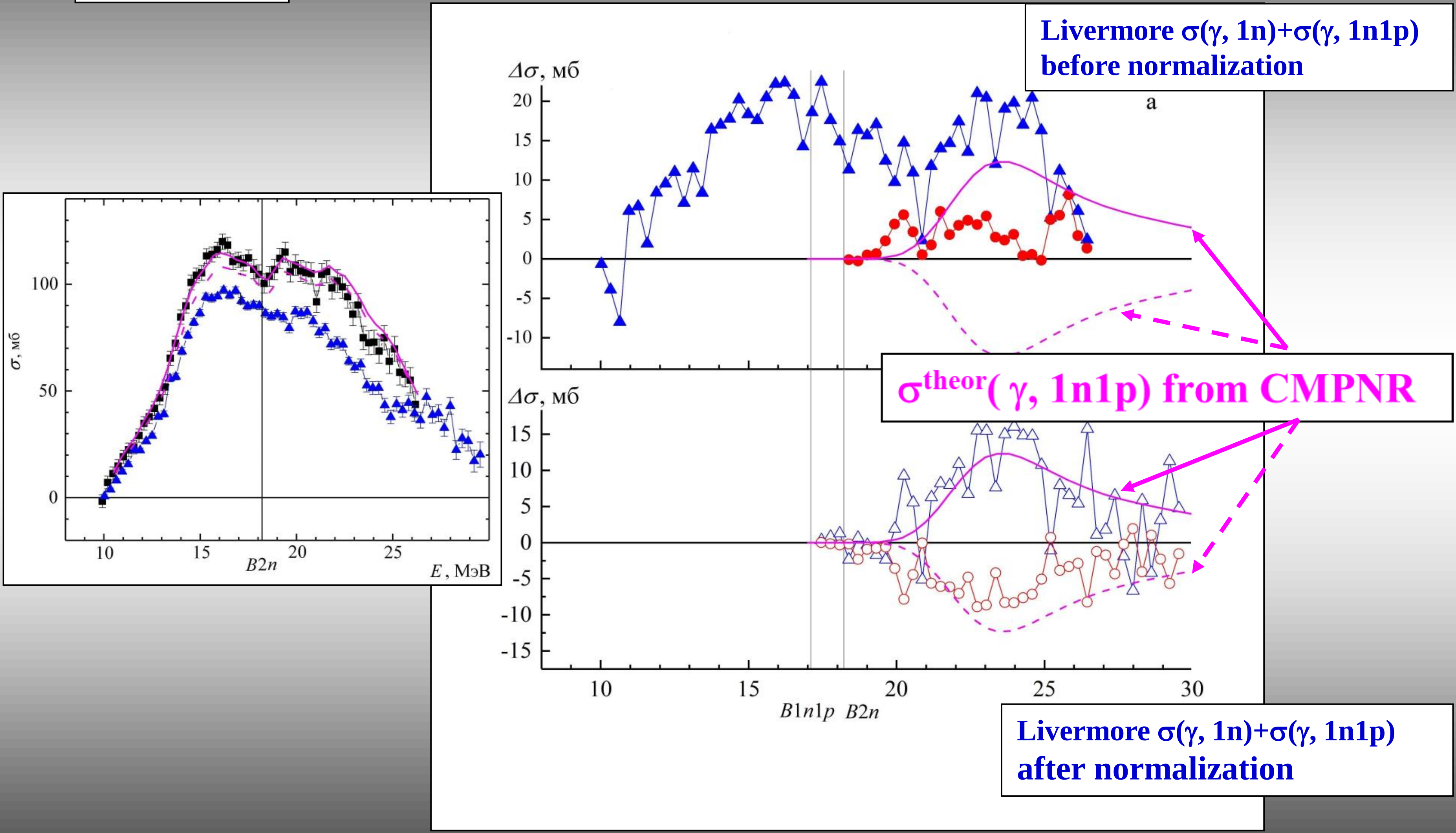
V.V.Varlamov et. al. Eur. Phys. J. A, 53 (2017) 180

σ^{theor}(γ, 1n1p) from CMPNR

Reliability criteria… systematic uncertainties
Критерии достоверности… систематические погрешности

^{75}As

Analogous conclusion was done concern Livermore experiment for ^{75}As [V.V.Varlamov et. al. Phys. Rev. C 99, N 2 (2019) 024608].



Livermore $\sigma(\gamma, 1n)+\sigma(\gamma, 1n1p)$ before normalization

$\sigma^{theor}(\gamma, 1n1p)$ from CMPNR

Livermore $\sigma(\gamma, 1n)+\sigma(\gamma, 1n1p)$ after normalization

CONCLUSIONS

There are noticeable systematic uncertainties of 3 kinds:

1. **There are significant systematic uncertainties for many (about 50) nuclei (^{51}V, ^{63,65}Cu, ^{75}As, ^{76,78,80,82}Se, ^{89}Y, ^{90,91,92,94}Zr, ^{103}Rh, ^{116,117,118,119,120,124}Sn, ^{115}In, ^{127}I, ^{129}Xe, ^{133}Cs, ^{138}Ba, ^{139}La, ^{140,142}Ce, ^{141}Pr, ^{145,148}Nd, ^{153}Eu, ^{159}Tb, ^{160}Gd, ^{165}Ho, ^{181}Ta, ^{186}W, ^{186,188,189,190,192}Os, ^{197}Au, ^{208}Pb, ^{209}Bi, and some others) in reaction cross sections from the shortcomings of the method for neutron multiplicity sorting concern because of unreliability of procedures used to separate counts of neutrons from (γ, 1n) and (γ, 2n) reactions.**

2. **Livermore data for ^{51}V, ^{75}As, and ^{59}Co contain significant systematic uncertainties from unreliable (erroneous) sorting of neutrons not only from (γ, 1n) and (γ, 2n) reactions, but from (γ, 1n1p) and (γ, 2n) reactions also.**

3. **Livermore data for ^{75}As, ^{127}I, ^{181}Ta, and ^{208}Pb contain significant systematic uncertainties from the loss of many neutrons from reaction (γ, 1n).**

CONCLUSIONS (continuation)

Because of noticeable disagreements between evaluated and experimental reaction cross sections the new re-analysis and re-evaluations are needed for various physical effects connected with processes with different number of outgoing neutrons :

- main GDR parameters (energy, amplitude, width);
- GDR isospin splitting parameters,…;
- competition between statistical and direct processes in GDR states decays;
- SUM RULE exhaustion.

Because presence of noticeable systematic uncertainties in experimental data obtained at both Livermore and Saclay using the methods of photoneutron multiplicity sorting other alternative methods for (γ, 1n), (γ, 2n), and (γ, 3n) reactions separation are needed.

Those could be the activation methods and methods of using the novel technique of direct neutron-multiplicity sorting with a flat-efficiency detector.

Thanks for attention!

Спасибо за внимание!

Theory (combined model)

Semiclassical exiton preequilibrium model of photonuclear reaction based on the Fermi gas densities and taking into account the effects of nucleus deformation and of GDR isospin splitting.

Bohr description of σ(*γ, lpkn*):

$$\sigma(\gamma, lpkn; E_\gamma) = \sum_i \sigma^{(i)}_{\text{ГДР}}(E_\gamma) W^{(i)}_{\text{ГДР}}(l,k,E_\gamma) + \\ + \sigma_{\text{КД}}(E_\gamma) W_{\text{КД}}(l,k,E_\gamma),$$

σ^i - one of 4 components (2 isospins - T_0 and $T_0 + 1$ and 2 directions of vibration),

σ_{GDR} - Lorenz lines with

$$\Gamma^{\downarrow}_{\text{рез}} \approx GI(a_0/R_0)[E_{\text{рез}} - \Delta(Z,N)\delta_{TT_>}]^2,$$

where

$$I(\xi) = \left[1 - 3\xi(1+\pi^2\xi^2/3)/(1+\pi^2\xi^2)\right] / (1+\pi^2\xi^2)$$

W - decay probabilities (recurrent):

$$W(l,k,E;dp,dn,m) = \hbar \sum_{j=n,p} \sum_{\substack{m'=m \\ \Delta m'=2}}^{\bar{m}-2} \frac{D(m',E;dp,dn,m)}{\Gamma^{\uparrow}(E;dp,dn,m') + \Gamma^{\downarrow}(E;dp,dn,m')} \times \\ \times \int_0^{E-B_j} \lambda_j(\varepsilon_j, E; dp, dn, m') W(l_j, k_j, U_j; dp_j, dn_j, m') d\varepsilon_j + \\ + D(\bar{m}, E; dp, dn, m) P(l,k,E;dp,dn),$$