# NEW
# PHOTONEUTRON REACTION CROSS SECTIONS FOR Pb ISOTOPES

# НОВЫЕ СЕЧЕНИЯ ФОТОНЕЙТРОННЫХ РЕАКЦИЙ ДЛЯ ИЗОТОПОВ Pb

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**The talk continues the discussions of the problems of reliability of the photonuclear data obtained in various experiments.**

**The main item of those problems is the presence of significant disagreements between photonuclear reaction cross sections obtained, first of all, using quasimonoenergetic photons and the method of neutron multiplicity sorting at Livermore (USA) and Saclay (France).**

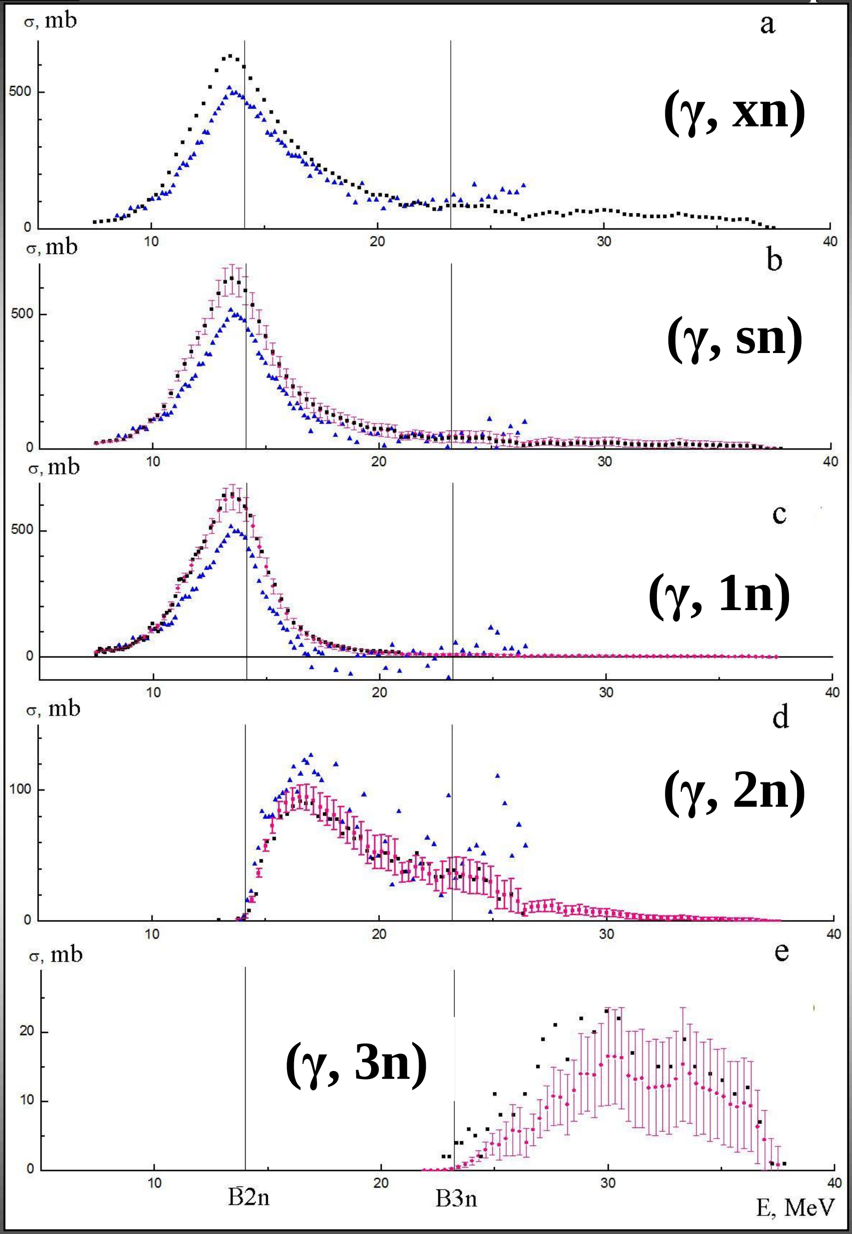
**This talk is devoted to the research of photodisintegration of $^{206,207}$Pb data for which were obtained only at Livermore basing on $^{208}$Pb data for which were obtained in various experiments.**

**Data for total and partial photoneutron reaction data are widely used in both basic and applied photonuclear research. Such kind data for magic (Z=82) Pb nuclei are very popular in comparison of the experimental reaction cross sections with those calculated in various theoretical models.**

**Isotope $^{208}$Pb is the most popular. Therefore many experiments were carried out for neutron yield reaction cross section σ(γ, xn) = σ(γ, 1n)+2σ(γ, 2n)+3σ(γ, 3n) in the case of $^{208}$Pb in various laboratories using various methods and incident γ-quanta beams including:**

- **bremsstrahlung,**
- **quasimonoenergetic photons obtained by annihilation in flight of relativistic positrons (Saclay (France), Livermore (USA),**
- **monoenergetic tagged photons,**
- **laser-Compton scattering γ-rays (NewSUBARU(Japan)),**
- **evaluation using the method of reduction.**

**At the same time the experimental data for the most demanded partial reactions cross sections σ(γ, 1n), σ(γ, 2n), and σ(γ, 3n) in the case of $^{208}$Pb were obtained only at Livermore and Saclay and in the cases of $^{206,207}$Pb - only at Livermore.**




## $^{208}$Pb

**In the case of isotope $^{208}$Pb there are significant (about several tens %) disagreements between Livermore and Saclay experimental data for all partial and total photoneutron reaction cross sections**

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

$$\sigma(\gamma, sn) = \sigma(\gamma, 1n)+\sigma(\gamma, 2n)+\sigma(\gamma, 3n),$$

$$\sigma(\gamma, 1n),$$

$$\sigma(\gamma, 2n)$$

$$\sigma(\gamma, 3n).$$

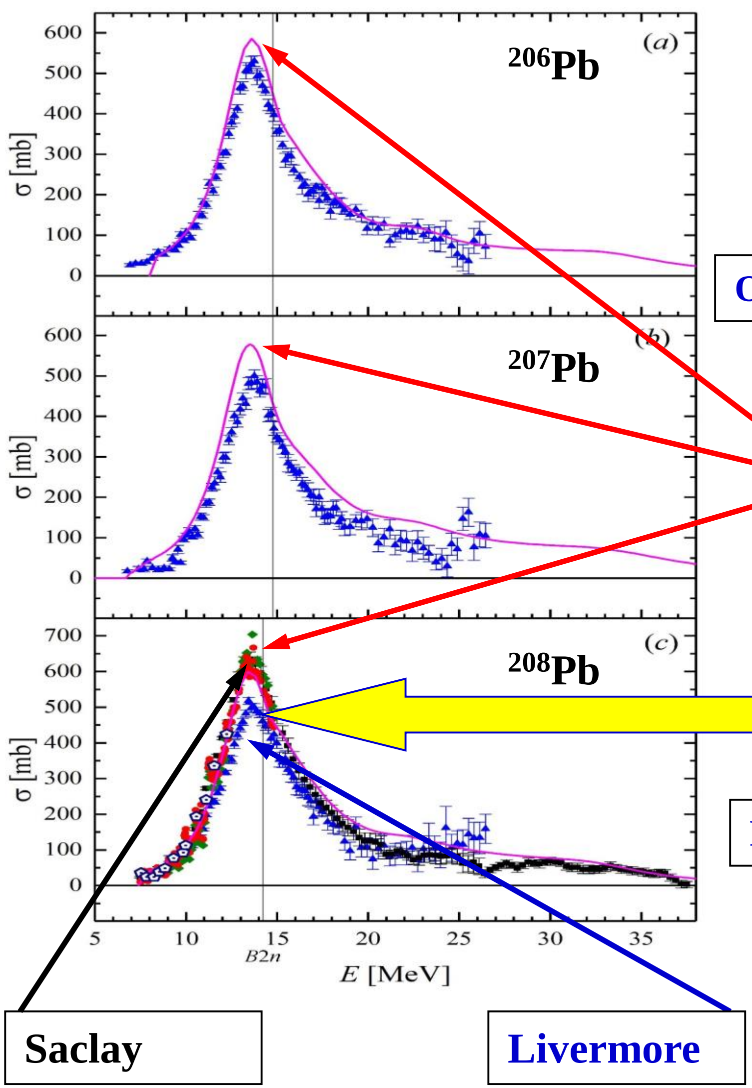
| Nucleus | Laboratory | Re-normalization factor |
|---|---|---|
| $^{nat}$Rb | Saclay | 0.85 ± 0.03 |
| $^{89}$Sr | Saclay | 0.85 ± 0.03 |
| $^{89}$Y | Saclay | 0.82 |
| $^{89}$Y | Livermore | 1.0 |
| $^{90}$Zr | Saclay | 0.88 |
| $^{90}$Zr | Livermore | 1.0 |
| $^{91}$Zr | Livermore | 1.0 |
| $^{92}$Zr | Livermore | 1.0 |
| $^{93}$Nb | Saclay | 0.85 ± 0.03 |
| $^{94}$Zr | Livermore | 1.0 |
| $^{127}$I | Saclay | 0.80 |
| $^{197}$Au | Saclay | 0.93 |
| $^{206}$Pb | Livermore | 1.22 |
| $^{207}$Pb | Livermore | 1.22 |
| *$^{208}$Pb* | *Livermore* | *1.22* |
| $^{208}$Pb | Saclay | 0.93 |
| $^{209}$Bi | Livermore | 1.22 |

To solve the problem of significant disagreements between Livermore and Saclay data at Livermore absolute photoneutron cross sections $\sigma^{exp}(\gamma, xn)$ for Zr, I, Pr, Au, and Pb were specially re-measured across the peak of the giant dipole resonance

B. L. Berman et al., Phys. Rev. C 36, 1286 (1987).

One can see the definite ambiguity of proposed recommendation because those re-normalizations were definitely individual and significantly different for many nuclei, in several cases opposite.
In the cases of data for $^{nat}$Rb, $^{89}$Sr, $^{89}$Y, $^{90}$Zr, $^{93}$Nb, $^{127}$I, $^{197}$Au, and $^{208}$Pb obtained at Saclay the proposed normalization factor is equal 0.80–0.93
(it means the decreasing Saclay data).

But in the cases of data for $^{206,207,208}$Pb normalization factors are equal to 1.22
(it vice versa means the increasing Livermore data).




**2 very important significant disagreements between data of various experiments in the case of neutron yield cross section**

$$\sigma(\gamma, xn) = \sigma(\gamma, 1n)+2\sigma(\gamma, 2n)+3\sigma(\gamma, 3n):$$

Only Livermore experiments for $^{206,207}$Pb

2. In the cases of all three isotopes $^{206,207,208}$Pb there are noticeable disagreements between Livermore experimental data and those calculated in the frame of the Combined PhotoNuclear Reactions Model (CPNRM) - lines.

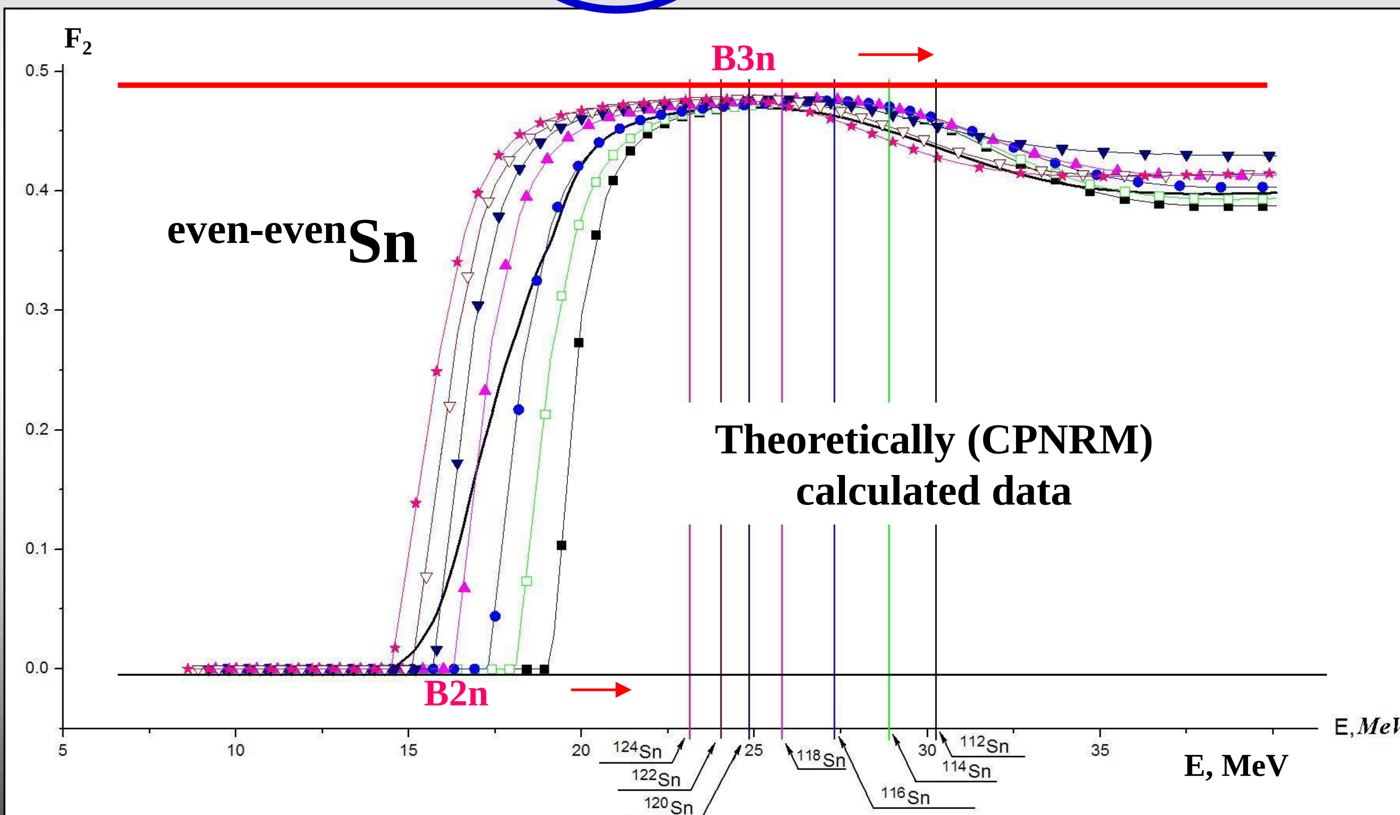
1. In the case of $^{208}$Pb all cross sections under discussion with exception of Livermore data are very close to each other.

Results of many experiments for $^{208}$Pb

**The main problem: nobody knows what data are reliable and could be recommended for using in both basic and applied research.**

# Main objective physical criterion for data reliability

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




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:

- $F_1 < 1.00$,
- $F_2 < 0.50$,
- $F_3 < 0.33$,
- $F_4 < 0.25$,
- $F_5 < 0.20$…

**The experimental-theoretical method of evaluation was proposed:**

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

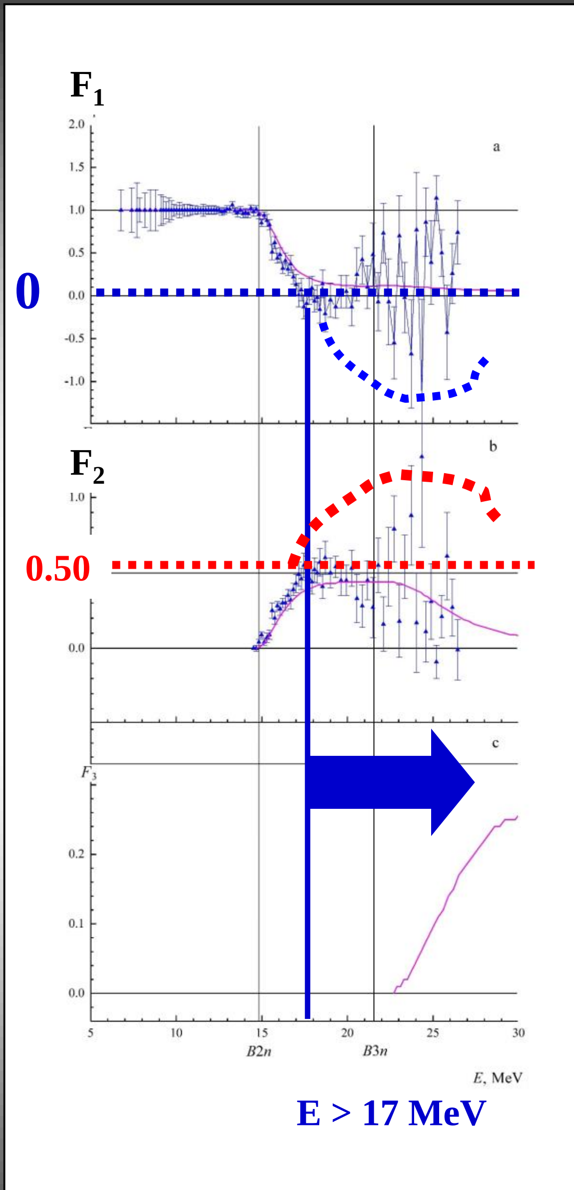
**This approach means that partial reactions (γ, 1n), (γ, 2n) and (γ, 3n) competitions are independent on the problems of experimental determination of neutron multiplicities in accordance with equations of model**

$$F_i^{theor} = \sigma^{theor}(\gamma, in)/\sigma^{theor}(\gamma, xn)$$

**and the correspondent sum of evaluated cross sections**

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

**is equal to the experimental $\sigma^{exp}(\gamma, xn) = \sigma^{exp}(\gamma, 1n)+2\sigma^{exp}(\gamma, 2n)+3\sigma^{exp}(\gamma, 3n)$ also relatively independent on neutron multiplicity problems because includes all produced neutrons.**




## $^{207}$Pb

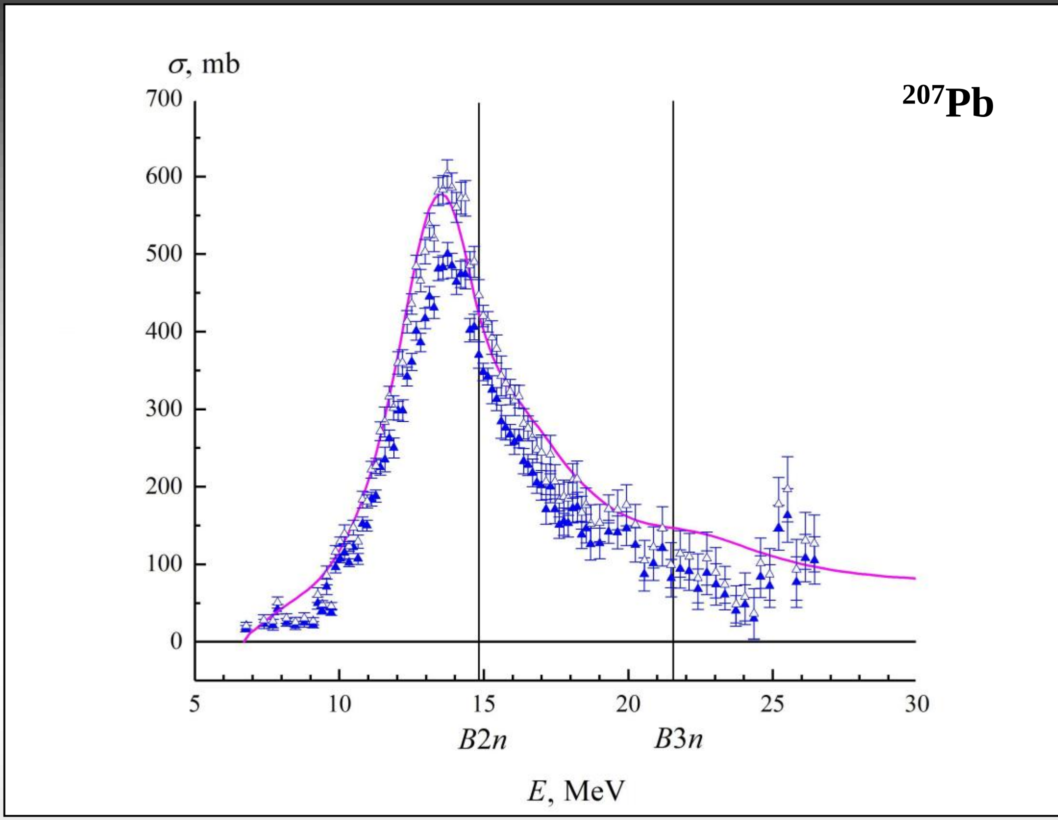
**There are serious doubts in experimental data reliability because in the energy range**

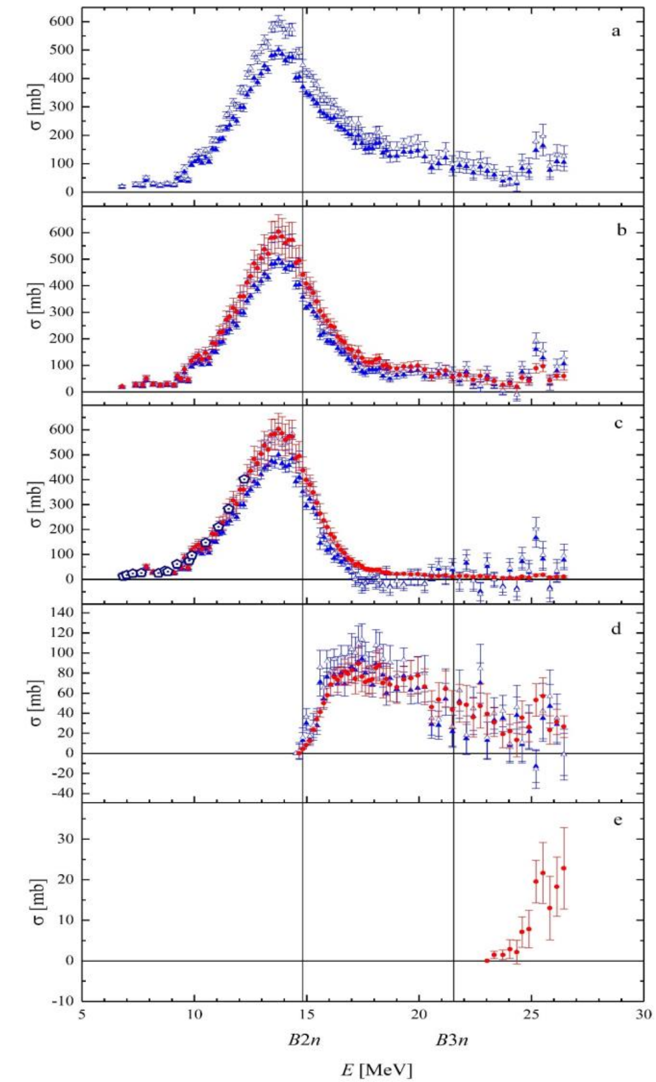
**E > 17 MeV**

**there are many physically forbidden $F_1^{exp} < 0$ values, many unreliable $F_2^{exp} > 0.50$ values and noticeable differences between $F_1^{exp}$ and $F_i^{theor}$ values.**

# New photoneutron reaction cross sections for Pb isotopes
# Новые сечения фотонейтронных реакций для изотопов Pb






**Kcorr = $\sigma^{theor}(\gamma, xn)/\sigma^{exp}(\gamma, xn)$ = 1846.6/1529.8 = 1.21.**

**Evaluated partial reaction cross sections were obtained using experimental data for σ(γ, xn) normalized to the cross section calculated in the CPNRM .**

# New photoneutron reaction cross sections for Pb isotopes
# Новые сечения фотонейтронных реакций для изотопов Pb



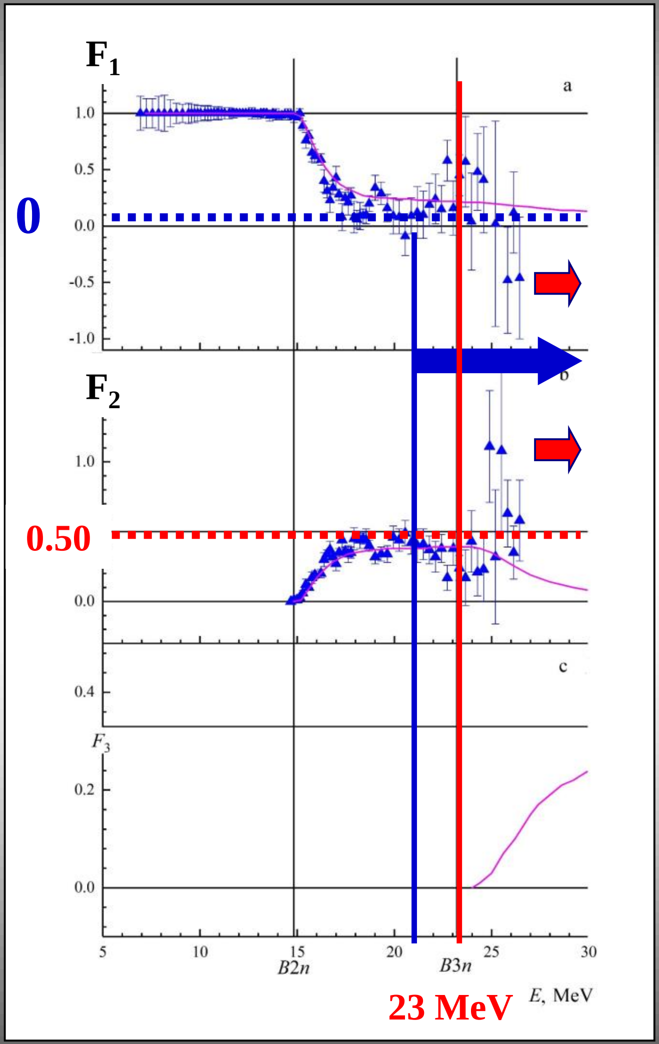
## $^{207}$Pb

| Reaction | Livermore | Evaluation | Livermore-corrected |
|---|---|---|---|
| $E^{int}$ = B2n = 14.8 MeV | | | |
| (γ, xn) | 1641.6 (8.8) | 1982.9 (10.6) | 1982.9 (10.6) |
| (γ, sn) | 1640.3 (8.7) | 1983.2 (29.6) | 1981.3 (10.5) |
| (γ, 1n) | 1633.1 (10.3) | 1982.9 (29.6) | 1972.6 (12.4) |
| $E^{int}$ = B3n = 21.6 MeV | | | |
| (γ, xn) | 2853.7 (18.8) | 3444.3 (22.7) | 3444.3 (22.7) |
| (γ, sn) | 2440.3 (15.2) | 3022.4 (34.85) | 2945.6 (18.3) |
| (γ, 1n) | 2002.1 (23.5) | 2598.9 (32.5) | ≈ 2416.9 (28.3) |
| (γ, 2n) | 413.4 (11.2) | 423.4 (12.8) | → 498.7 (13.4) |
| $E^{int}$ = 26.4 MeV | | 18% | |
| (γ, xn) | 3268.1 (30.3) | 3945.0 (36.6) | 3945.0 (36.6) |
| (γ, sn) | 2717.5 (23.5) | 3281.4 (38.4) | 3280.3 (28.3) |
| (γ, 1n) | 2133.6 (38.4) | 2648.9 (32.7) | ≈ 2575.4 (46.3) |
| (γ, 2n) | 550.6 (19.2) | 599.6 (19.7) | → 664.7 (23.2) |
| (γ, 3n) | | 32.8 (3.8) | 13% |

**The simple normalization of data does not give the solution of systematic disagreements problems:**

**better agreement for (γ, 1n) reaction is accompanied by increasing disagreement for (γ, 2n) reaction.**

# $^{206}$Pb



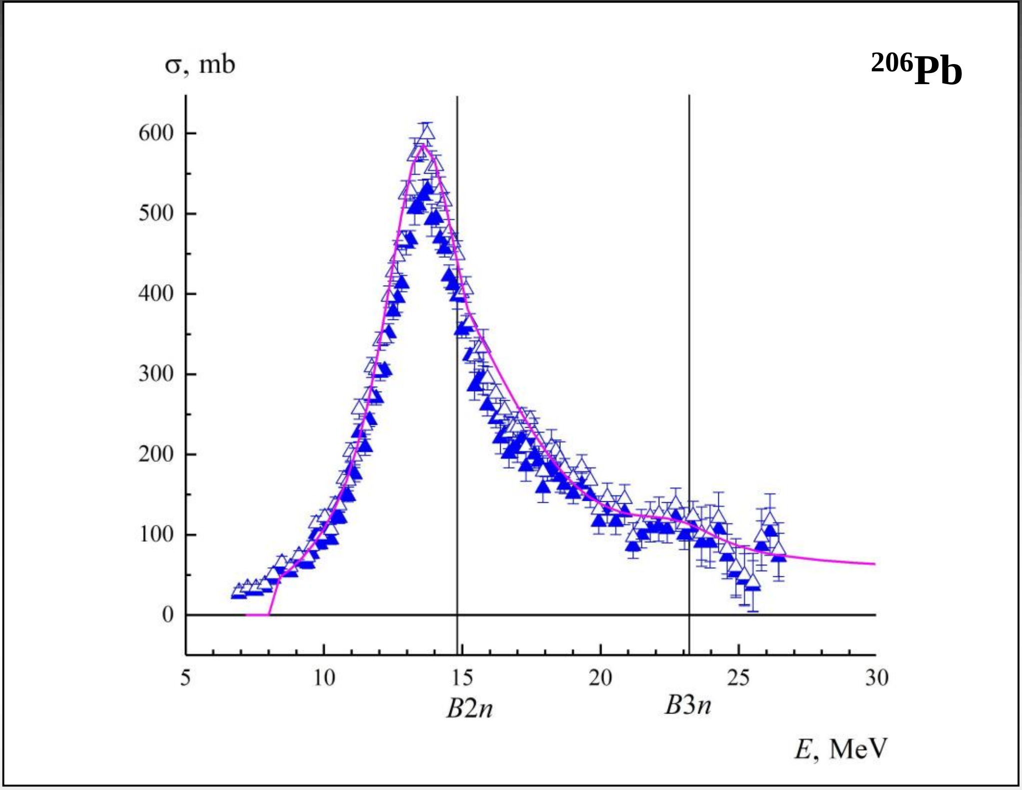

**One can see that in this case at the energies up to $B3n$ = 23.2 MeV there are no noticeable unreliable $F_1^{exp} < 0$ values or $F_2^{exp} > 0.50$ values.**

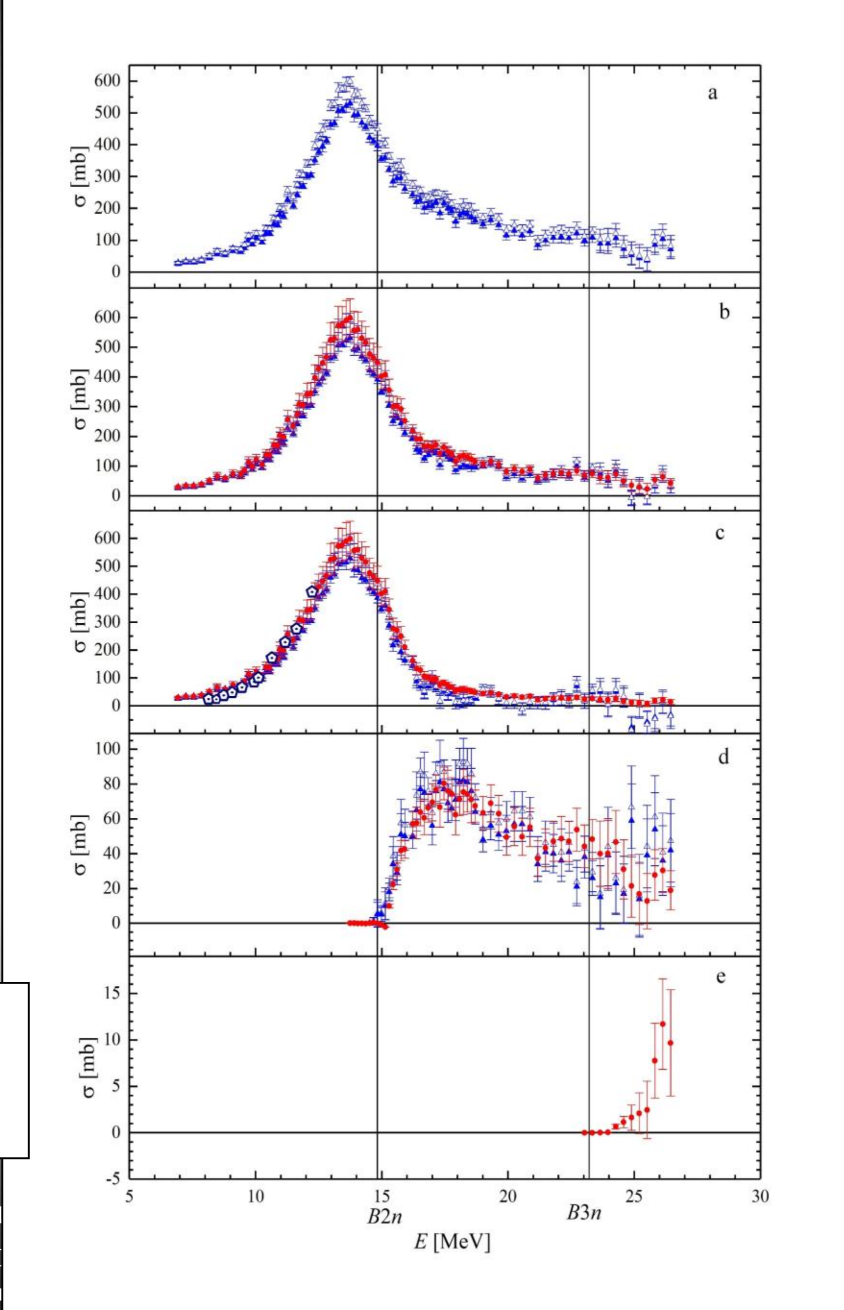
**At the same time at energies higher ~21 MeV there are noticeable differences between $F_i^{exp}$ and $F_i^{theor}$.**

**Additionally it must be pointed out that at energies higher ~ 23 MeV dependences on photon energies of both $F_1^{exp}$ and $F_2^{exp}$ are very strange.**

# New photoneutron reaction cross sections for Pb isotopes
# Новые сечения фотонейтронных реакций для изотопов Pb






**Kcorr = $\sigma^{theor}(\gamma, xn)/\sigma^{exp}(\gamma, xn)$ = 1927.4/1705.9 = 1.13.**

**Evaluated partial reaction cross sections were obtained using experimental data for σ(γ, xn) normalized to the cross section calculated in the CPNRM .**

# New photoneutron reaction cross sections for Pb isotopes
# Новые сечения фотонейтронных реакций для изотопов Pb



## $^{206}$Pb

| Reaction | Livermore | Evaluation | Livermore-corrected |
|---|---|---|---|
| $E^{int}$ = B2n = 14.8 MeV | | | |
| (γ, xn) | 1761.9 (8.2) | 1992.2 (9.3) | 1992.2 (9.3) |
| (γ, sn) | 1761.3 (8.2) | 1992.2 (28.4) | 1991.6 (9.3) |
| (γ, 1n) | 1757.6 (9.2) | 1992.2 (28.4) | 1987.2 (10.4) |
| $E^{int}$ = B3n = 23.2 MeV | | | |
| (γ, xn) | 3224.6 (17.5) | 3643.9 (19.8) | 3643.9 (19.8 |
| (γ, sn) | 2799.1 (14.6) | 3201.0 (33.5) | 3162.8 (16.4) |
| (γ, 1n) | 2322.1 (21.4) | 2758.3 (31.9) | ≈ 2623.9 (24.2) |
| (γ, 2n) | 426.4 (9.8) | 442.7 (10.4) | → 481.8 (10.9) |
| $E^{int}$ = 26.4MeV | | | 10% |
| (γ, xn) | 3478.5 (27.2) | 3930.6 (30.8) | 3930.6 (30.8) |
| (γ, sn) | 2947.5 (21.5) | 3368.4 (36.2) | 3330.7 (24.3) |
| (γ, 1n) | 2321.7 (33.8) | 2816.6 (32.6) | ≈ 2623.9 (38.2) |
| (γ, n) | 532.6 (16.7) | 541.8 (15.6) | → 601.6 (18.9) |
| (γ, 3n) | | 10.0 (1.9) | 12% |

In complete analogy to the case of $^{207}$Pb

**the better agreement for (γ, 1n) reaction is accompanied by increasing disagreement for (γ, 2n) reaction.**

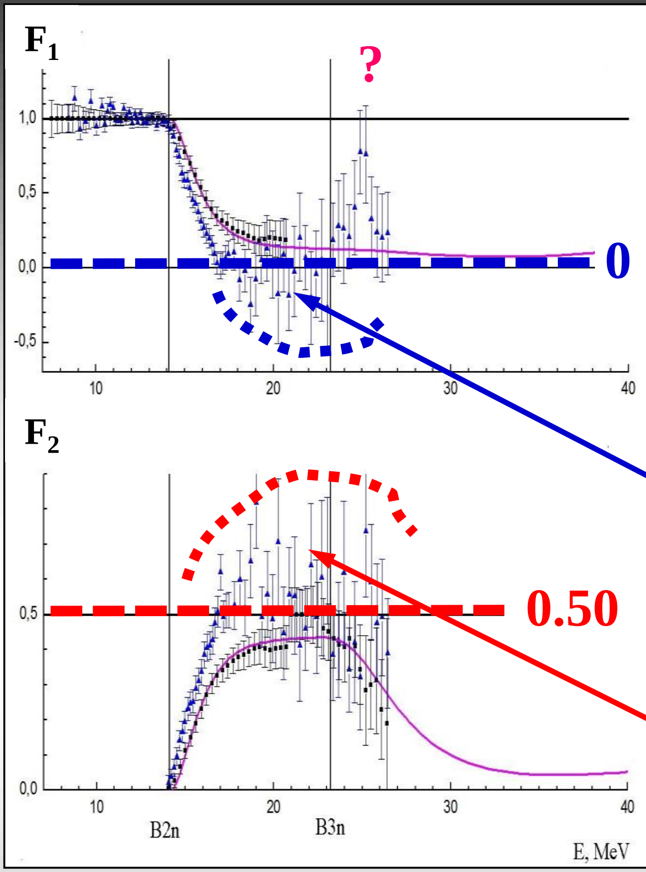
**Using the new evaluated data for various photoneutron reactions for $^{206,207}$Pb one is forced to conclude that in the cases of both isotopes :**

1) **the Livermore neutron yield cross sections σ(γ, xn) are significantly underestimated in comparison with the results calculated in the CPNRM.**
2) **the Livermore experimental cross sections σ(γ, 1n) and σ(γ, 2n) do not satisfy physical data reliability criteria.**
3) **the traditional simple normalization does not solve the problem of systematic disagreements under discussion because this procedure decrease the disagreement in the case of σ(γ, 1n) but increase that in the case of σ(γ, 2n).**

**The reasons of data unreliability in the cases of $^{206,207}$Pb can be explained using the previous data for $^{208}$Pb by very specific competitions between σ(γ, xn), σ(γ, sn), σ(γ, 1n) and σ(γ, 2n) cross sections.**

# $^{208}$Pb

# Nucleus-2020 results

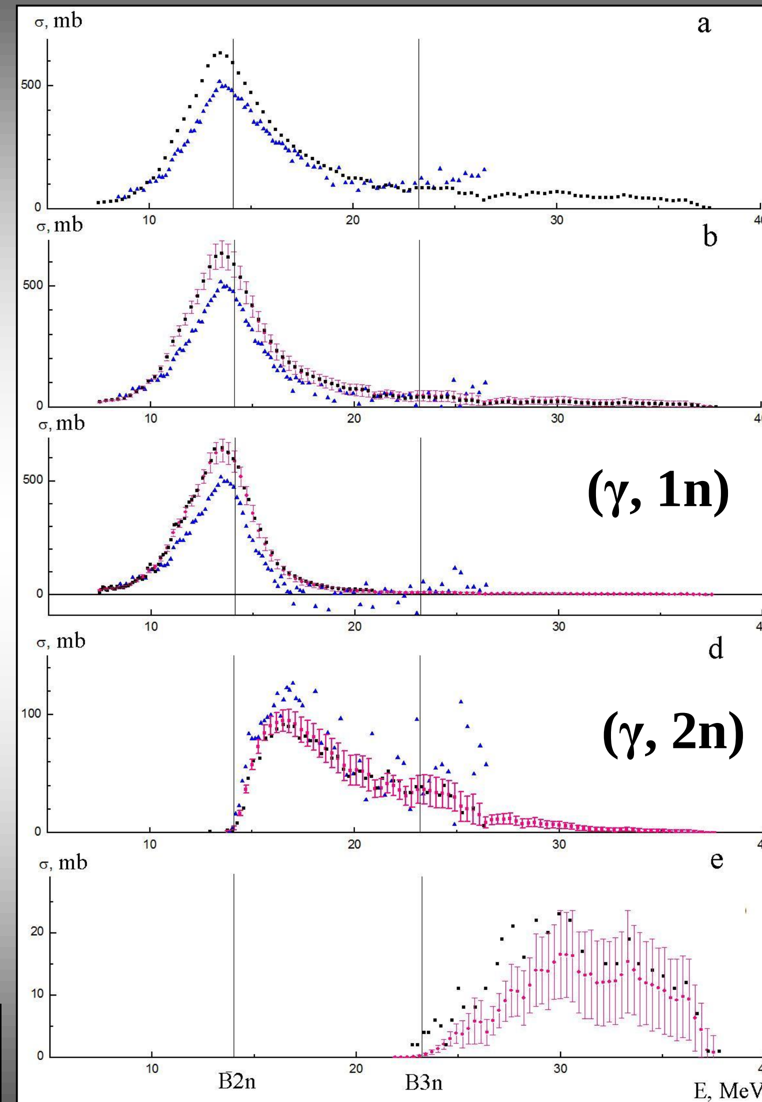



**Unreliable data:**

**physically forbidden negative values**

**and**

**values for which $F_2 > 0.50$**




**Unreliable partial Livermore cross sections for both (γ, 1n) and (γ, 2n) reactions.**

**Phys. Atom. Nucl. 76, 1403 (2013)**

**Significant disagreements between Livermore and evaluated cross sections.**

## $^{208}$Pb (integrated cross sections $\sigma^{int}$)

Phys. Atom. Nucl. 76, 1403 (2013)

| Reaction | Livermore | | Saclay | | Evaluation |
|---|---|---|---|---|---|
| $E^{int}$ = B2n = 14.1 MeV | | | | | |
| (γ, xn) | 1432.9 | < 26% | 1811.1 | 0% | 1811.1 |
| (γ, sn) | 1431.0 | | 1811.1 | | 1791.8 |
| (γ, 1n) | 1432.3 | | 1810.7 | | 1791.4 |
| $E^{int}$ = B3n = 23.2 MeV | | | | | |
| (γ, xn) | 3186.7 | < 20% | 3820.8 | 0% | 3820.8 |
| (γ, sn) | 2508.2 | < 30% | 3299.4 | ≈ | 3270.9 |
| (γ, 1n) | 1922.0 | < 40% | 2817.1 | >4% | 2699.6 |
| (γ, 2n) | 670.9 | >15% | 530.0 | <7% | 571.2 |

**Significant disagreements between experimental and evaluated cross sections**

**Very strange competitions between partial reaction cross sections**

# Nucleus-2020 results

**Significant disagreement between evaluated and experimental data in the case of Livermore**
**and small once in the case of Saclay.**

In the transitions

**(γ, xn) → (γ, sn) → (γ, 1n)**

the differences between Livermore and evaluated $\sigma^{int}$ values systematically increase (from 20% to 40%),

but in the transition

**(γ, 1n) → (γ, 2n)**

this difference became significantly smaller (15%).

This is not in case of Saclay data.

# Nucleus-2020 results

| Nucleus / Reaction | | $\sigma^{int}_{eval}/\sigma^{int}_{L}$ | | |
|---|---|---|---|---|
| | $^{75}$As | $^{127}$I | $^{181}$Ta | $^{208}$Pb |
| (γ, xn) | 1.27 | 1.20 | 1.24 | 1.20 |
| (γ, sn) | 1.30 | 1.25 | 1.30 | 1.30 |
| (γ, 1n) | 1.34 | 1.33 | 1.46 | 1.40 |
| (γ, 2n) | 1.14 | 0.98 | 1.05 | 0.85 |

The larger the fraction of the simple σ(γ, 1n) reaction in the cross-section for the complex reactions the higher the degree to which the latter is underestimated in comparison with evaluated one.

(γ, xn) = (γ, 1n) + [2(γ, 2n) + 3(γ, 3n) + …]
some contribution of (γ, 1n) reaction

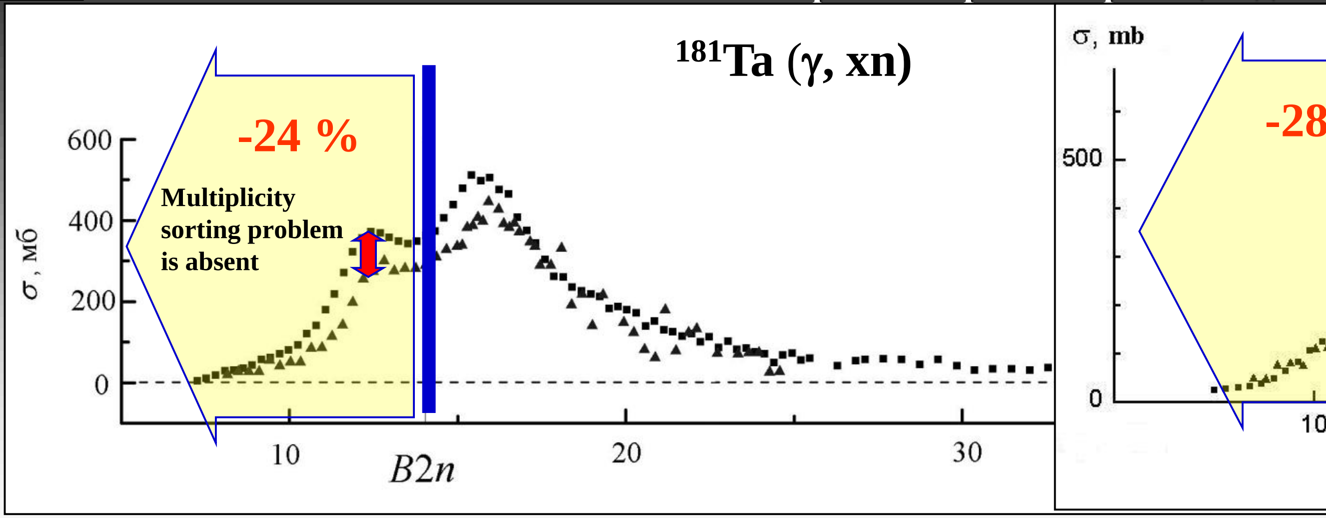
(γ, sn) = (γ, 1n) + [(γ, 2n) + (γ, 3n) + …]
larger contribution of (γ, 1n) reaction

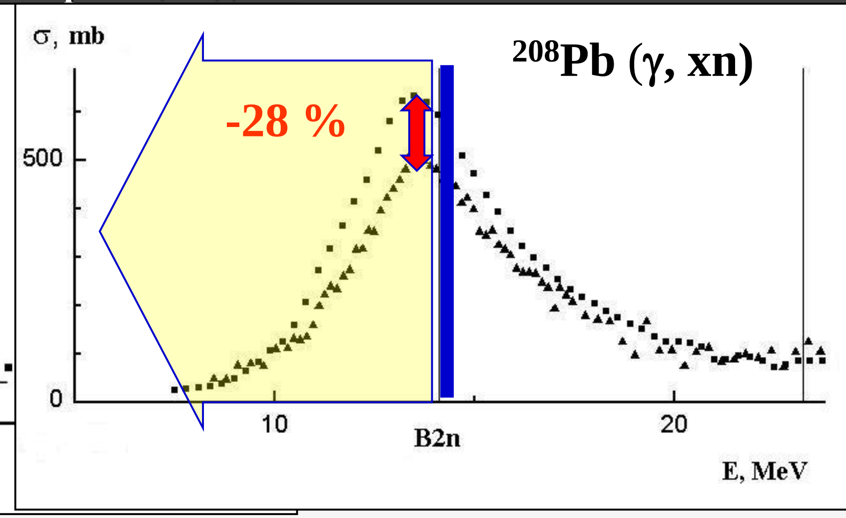
(γ, 1n) = (γ, 1n) + [0]
maximal 100%-contribution of (γ, 1n) reaction

(γ, 2n) [0]
zero contribution of (γ, 1n) reaction

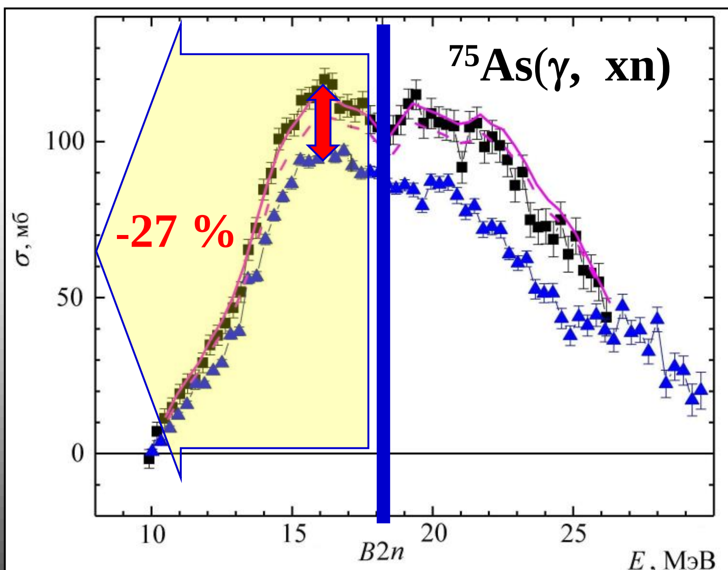
The very large underestimation of the cross-section for reaction (γ, 1n) is responsible for a substantial underestimations of the cross-section for the reaction (γ, xn).

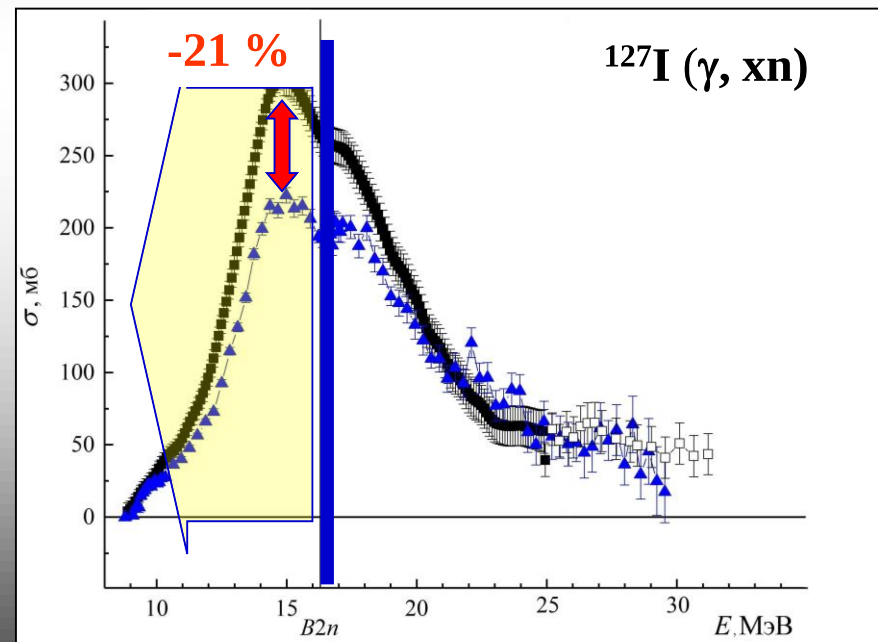
One is forced to conclude that in Livermore experiments many neutrons from (γ, 1n) reaction were lost. This could be resulted from some problem of neutron detection efficiency at different neutron energies.



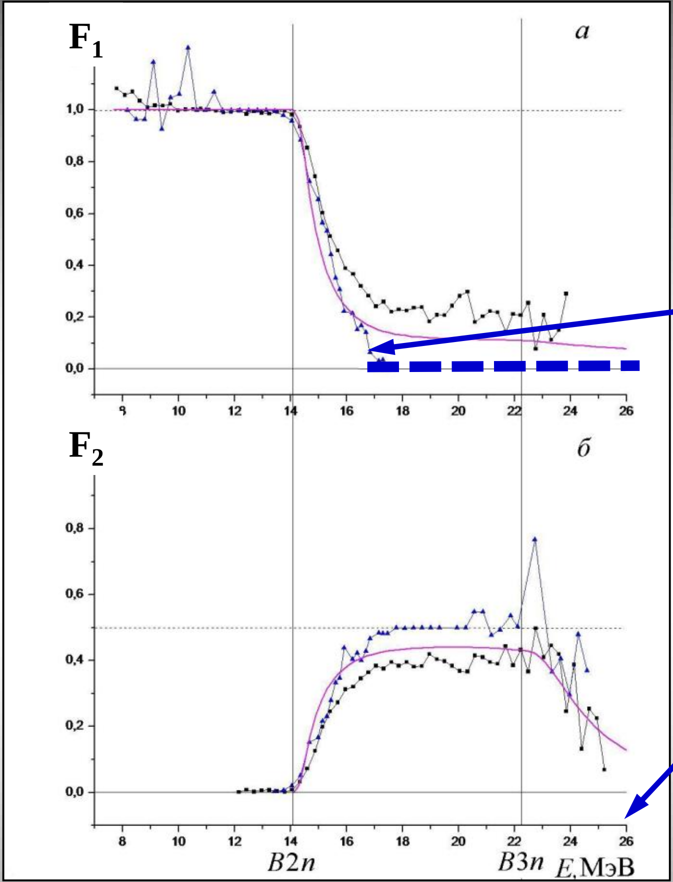




# Nucleus-2020 results



$^{181}$Ta




## Natural explanation: many neutrons from (γ, 1n) reaction were lost.

At Livermore no neutrons from (γ, 1n) reaction were detected for photon energies E > 18.5 MeV

but

at the same time neutrons from (γ, 2n) reaction were detected up to energy near 25 MeV.

It could be in case only if many neutrons from (γ, 1n) reaction (all of those at energies E > 18.5 MeV) were lost.

That is why the competitions between partial reactions became unreliable and the simple normalization could not solve the problem of significant systematic disagreements under discussion.

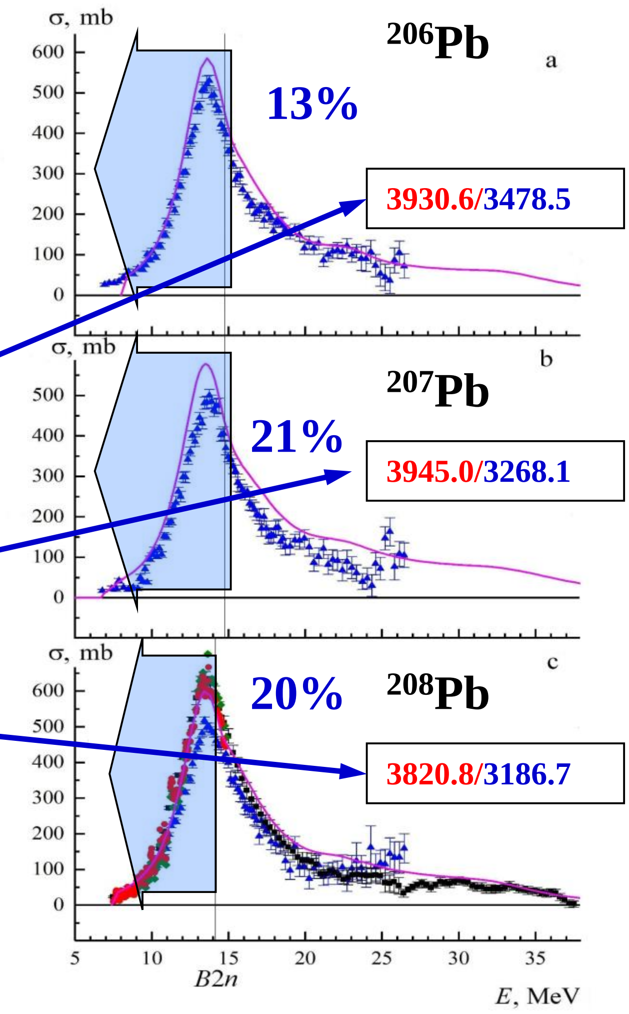
The reason of the loss of all neutrons at the photon energies higher ~ 17.5 MeV could be some problem of neutron detection efficiency.

**Absolutely the same situations are in the cases of $^{206,207}$Pb.**

**At energies below the thresholds B2n of (γ, 2n) reaction cross sections of reactions (γ, xn), (γ, sn), and (γ, 1n) must be identical but...**
**The reason is that many neutrons from (γ, 1n) were lost.**

| | $\sigma^{int}_{eval}/\sigma^{int}_{L}$ | | |
|---|---|---|---|
| Nucleus Reaction | $^{206}$Pb | $^{207}$Pb | $^{208}$Pb |
| (γ, xn) | 1.13 | 1.21 | 1.20 |
| (γ, sn) | 1.15 | 1.24 | 1.30 |
| (γ, 1n) | 1.19 | 1.30 | 1.40 |
| (γ, 2n) | 1.02 | 1.02 | 0.85 |

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



## SUMMARY AND CONCLUSIONS

1. It was shown that the experimental photoneutron reaction cross sections for $^{206,207}$Pb isotopes do not satisfy the objective physical criteria.

2. New reliable data for partial (γ, 1n), (γ, 2n) and total (γ, sn), (γ, xn) reaction cross sections for $^{206,207}$Pb were evaluated using experimental-theoretical method basing on data reliability criteria.

3. It was obtained that the experimental Livermore cross sections for $^{206,207}$Pb, as well as for $^{208}$Pb, are significantly underestimated in comparison with the evaluated once. Those disagreements could not be excluded using the traditional simple experimental data normalization.

4. It was found that the Livermore (γ, xn), (γ, sn), and (γ, 1n) reaction cross sections for $^{206,207,208}$Pb, as well as for $^{75}$As, $^{127}$I, and $^{181}$Ta, contain significant systematic uncertainties from the loss of many neutrons from reaction (γ, 1n). This is why those data are not reliable and could not be recommended for using in estimation of Giant Dipole Resonance parameters and in various applications.

# Thanks a lot for attention!

# Спасибо большое за внимание!

# Combined Photonucleon Reaction Model (CPNRM)

**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*):**

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

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

**$\sigma_{GDR}$ - Lorenz lines with**

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

**where**

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

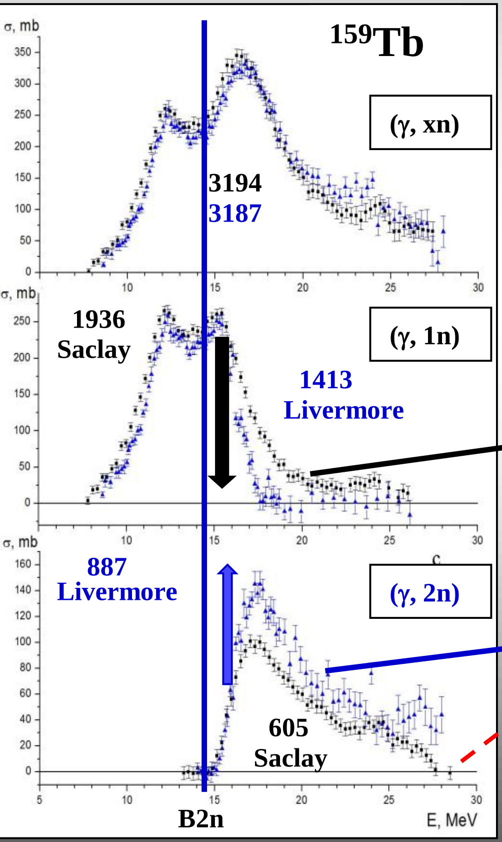
**W - decay probabilities (recurrent):**

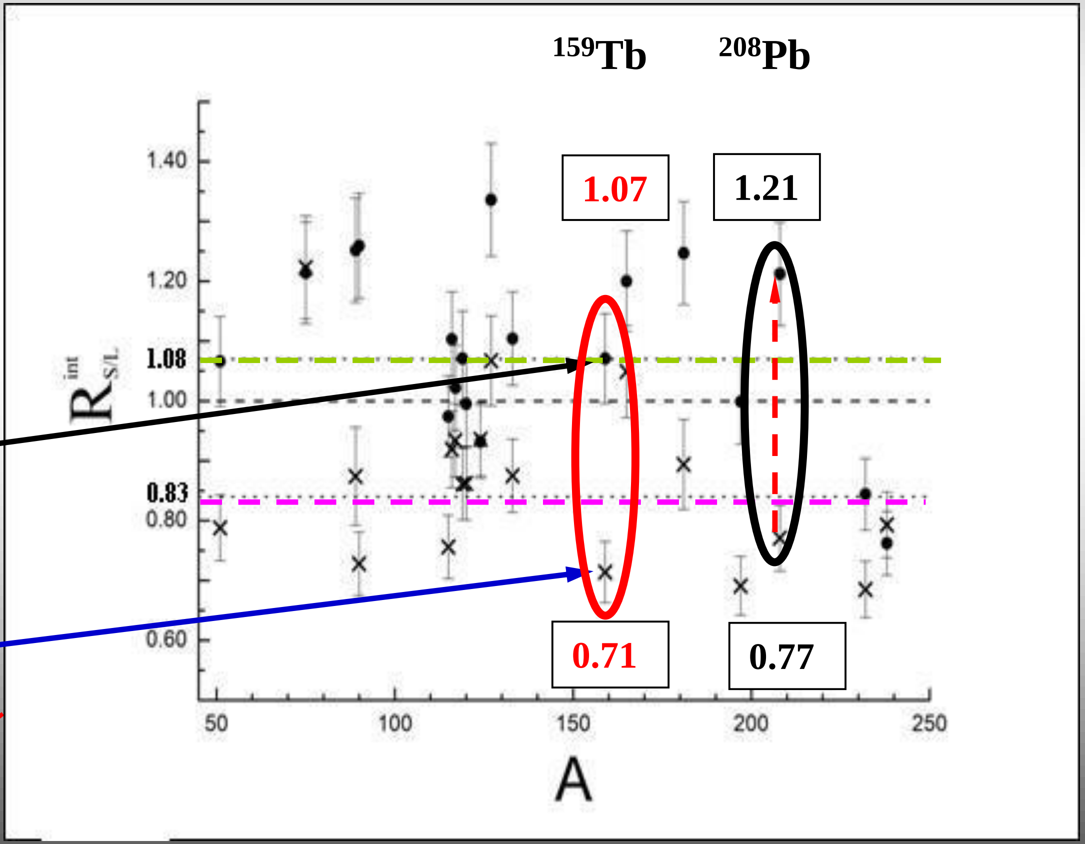
$$W(l,k,E;dp,dn,m) = \hbar \sum_{j=n,p} \sum_{\substack{m'=m \\ \Delta m'=2}}^{\bar{m}-2} \frac{D(m',E;dp,dn,m)}{\Gamma^{\uparrow}(E;dp,dn,m') + \Gamma^{\downarrow}(E;dp,dn,m')} \times \\ \times \int_0^{E-B_j} \lambda_j(\varepsilon_j,E;dp,dn,m') W(l_j,k_j,U_j;dp_j,dn_j,m') d\varepsilon_j + \\ + D(\bar{m},E;dp,dn,m)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

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.

**Nucleus-2020 results**

**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.