Photonuclear Reactions: Systematical Disagreements, Methods of Their Overcoming and Physical Consequences

B.S.Ishkhanov, V.V.Chesnokov, N.N.Peskov, M.E.Stepanov, and V.V.Varlamov

Skobeltsyn Institute of Nuclear Physics and Physics Department of Lomonosov Moscow State University,
Leninskie Gory, 119992 Moscow, Russia

Abstract. There are many clear systematical disagreements both in shape and magnitude between data obtained in different experiments decreased data accuracy and reliability. The systematical overview of photonuclear reaction cross section values obtained at various experiments, first of all that from experiments with bremsstrahlung and quasimonoenergetic annihilation photons has been carried out and used for discussion of the data modern status. It was found out that as a rule both total and partial photoneutron reaction cross sections obtained systematically differ each other. Significant discrepancies between photonuclear reaction cross sections obtained at various experiments were analyzed jointly. The disagreements of partial reaction cross section data were interpreted as the result of difference of neutron multiplicity sorting procedures used. The special method was used to move the data into consistence. Joint analysis of the (γ,xn), (γ,n) and (γ,2n) reaction cross section data obtained at both laboratories mentioned was carried out for 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. Consistent data were evaluated. Some important physical consequences were pointed out.

INTRODUCTION

Absolute majority of photonuclear reaction cross section data have been obtained[1–5] using bremsstrahlung (BR) and quasimonoenergetic photons from annihilation (QMA) in flight of relativistic positrons at USA National Lawrence Livermore Laboratory and France Centre d'Etudes Nucleaires de Saclay. Clear disagreements both in shape and magnitude between data obtained using not only different but the same methods have been found out. Those are more largely than statistical uncertainties and systematical certainly: they very clear depend on the experimental method used. Though majority of photonuclear reaction cross section data has been obtained quite long ago they are included into the modern database[6] and extensively used till now. Therefore modern status of photonuclear research as whole and accuracy and reliability of each data obtained can be understandable only on the analysis of systematical disagreements and of the ways to take them into account. The big database /http://cdfe.sinp.msu.ru/exfor/index.php/ developed gives to one possibility for systematical overview of all data collected jointly and analysis of various discrepancies between of them.

The main aims of this work were:

- Investigation of such data discrepancies in absolute value systematically,
- Finding out their sources and develop the methods for their taking into account and putting various experiments data into accordance with each other,
- Formulating clear recommendations for achievement the balance between data of various experiments.

For that first of all Saclay-Livermore total photoneutron (γ,xn) and partial photoneutron (γ,n) and (γ,2n) reaction cross section data discrepancies were analyzed in details jointly.

TWO MAIN TYPES OF PHOTONUCLEAR EXPERIMENTS

Bremsstrahlung (BR) Experiments

Bremsstrahlung spectrum is continuous and therefore not direct reaction cross section is measured in experiment but only reaction yield $Y(E_{jm},k)$ - cross section $\sigma(k)$ with threshold E_{th} depended on photon energy k folded with photon spectrum $W(E_{jm},k)$ with end-point energy E_{jm}:

$$Y(E_{jm}) = \frac{N(E_{jm})}{\varepsilon D(E_{jm})} = \alpha \int_{Eth}^{Ejm} W(E_{jm},k)\sigma(k)dk. \qquad (1)$$

Cross section σ can be obtained from the yield Y using one of well-known mathematician methods ("Photon difference", "Penfold-Leiss", " Cook least structure", "Tikhonov regularization", etc.).

Quasimonoenergetic annihilation (QMA) Experiments

QMA-experiments[1,5)] use the process of producing annihilation photons with energy $E_\gamma = E_{e+} + 0.511$ MeV by fast positrons. Annihilation photons always are accompanied by positron bremsstrahlung: 3 steps are needed - 1) measurement of yield $Y_{e+}(E_j,k)$ of reaction induced by photons from e^+ both annihilation and bremsstrahlung; 2) measurement of yield $Y_{e-}(E_j,k)$ of reaction induced by photons from e^- bremsstrahlung; 3) yields subtraction and interpretation of difference obtained as reaction cross section "measured directly"

$$Y_{e+}(E_j,k) - Y_{e-}(E_j,k) = Y(E_j,k) \approx \sigma(k). \qquad (2)$$

It must be pointed out that: 1) there is no beam of QMA-photons in reality: they are arising as two real spectra difference only; 2) apparatus function of experiment is obtained individually because depends on both measurements (yields - Y_{e+}, Y_{e-}) conditions; 3) e^+ annihilation occurs in many steps (bremsstrahlung production ($e^-+A \rightarrow A+e^-+\gamma$); pairs production ($\gamma+A \rightarrow A+e^-+e^+$); positron annihilation ($e^++e- \rightarrow 2\gamma$)); therefore number of quasimonoenergetic photons, measured yields statistical accuracy, and hence their normalization accuracy are small.

MAIN DISAGREEMENTS OF REACTION CROSS SECTIONS

Total Photoneutron Reaction (γ,xn)

Integrated cross section data.

There are definite discrepancies in absolute value between data obtained at different laboratories using both BR- and QMA-photons. Several examples are presented in Table 1. These four of many cases$^{1)}$ were taken because close integration energy limits $E_\gamma^{\text{int-max}}$ or vise versa integrated cross section values σ^{int}. One can easily estimate that values obtained at Saclay are higher than that obtained at Livermore for about 6 – 16 %. Many other similar discrepancies exist$^{1)}$ but are not so clear because of big differences in $E_\gamma^{\text{int-max}}$.

TABLE 1. Comparison of QMA-experiments Integrated Total Photoneutron Reaction Cross Section Data of Saclay-to-Livermore $\sigma^{\text{int}}{}_{\text{s}}/\sigma^{\text{int}}{}_{\text{L}}$ Values

Nucleus	**^{51}V**	**^{75}As**	**^{90}Zr**	**^{165}Ho**
$E_\gamma^{\text{int-max}}$ (MeV)	**27.8/27.8**	**26.2/29.5**	**25.9/27.6**	**26.8/28.9**
$\sigma^{\text{int}}{}_{\text{s}}/$	**689/654**	**1306/1130**	**1309/1158**	**3667/3385**
$\sigma^{\text{int}}{}_{\text{L}}$	**= 1.06**	**≥ 1.16**	**≥ 1.13**	**≥ 1.08**

Integrated cross section data systematic.

The complete systematic of integrated cross sections ratios was obtained$^{7)}$ for (γ,xn) = [(γ,n) + (γ,np) + 2(γ,2n)] reaction cross section data for energy ranges between the (γ,n) and (γ,2n) reaction thresholds. Special ratios $R^{int}_{syst} = \sigma^{int}_{various\ labs}(\gamma,xn)/\sigma^{int}_{Livermore}(\gamma,xn)$ of data from various laboratories to that from Livermore are presented on Fig. 1. Data confirm clearly definite that Livermore cross sections as a rule are smaller than others – ratios analyzed are concentrated near the mean value $\langle R^{int}_{syst}\rangle = 1.12$. It's important to point out that QMA-data obtained at Saclay are more consistent with data (both QMA- and BR-) of other laboratories than with Livermore QMA-data.

Reaction cross section absolute values. Photoneutron reaction cross sections for nuclei ^{nat}Zr, ^{127}I, ^{141}Pr, ^{197}Au, and ^{nat}Pb obtained earlier at Livermore have been specially remeasured$^{8)}$ and used for detailed comparison of absolute values of photoneutron reaction cross sections for 15 nuclei from Rb to Bi. Significant Livermore-Saclay disagreements have been found out and special coefficient F = 0.85 – 1.22 was proposed for normalization.

As an explanation of appreciable discrepancies between the data obtained at Livermore and Saclay, it was pointed out$^{8)}$ that "…this comparison implies an Livermore experiments error either in the photon flux determination or in the neutron detection efficiency or in both". The major recommendations to put data into consistency were dual certainly: 1) decrease Saclay data for Rb, Sr, Y, ^{90}Zr, Nb, ^{127}I, ^{197}Au, ^{208}Pb by factor F = 0.8 – 0.93; 2) increase Livermore data for ^{206,207,208}Pb, ^{209}Bi by factor 1.22 (to achieve agreement with data obtained using tagged photons). It must be pointed out that mean value $\langle 1/F\rangle = 1.16 \approx \langle R^{int}_{syst}\rangle = 1.12$.

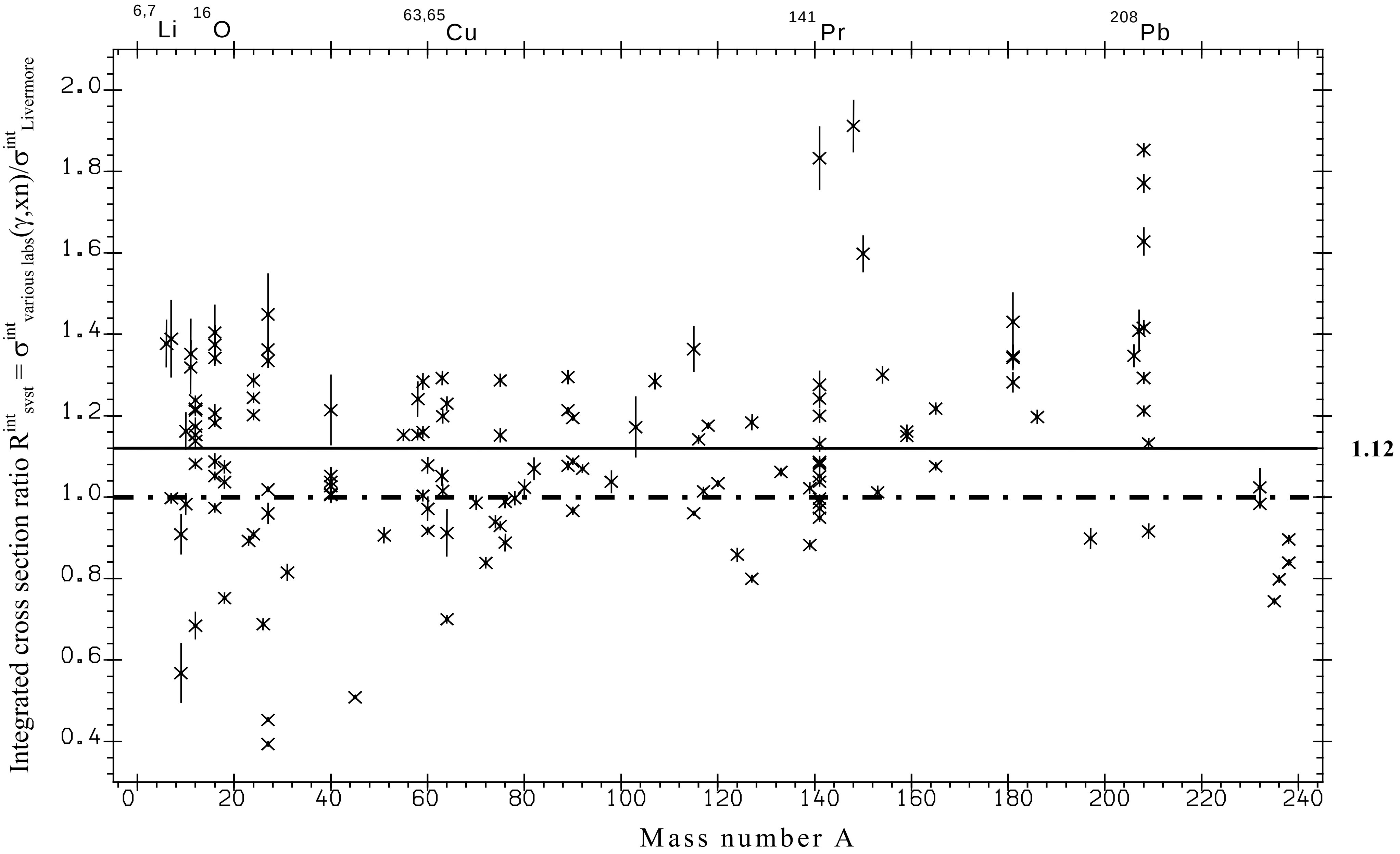


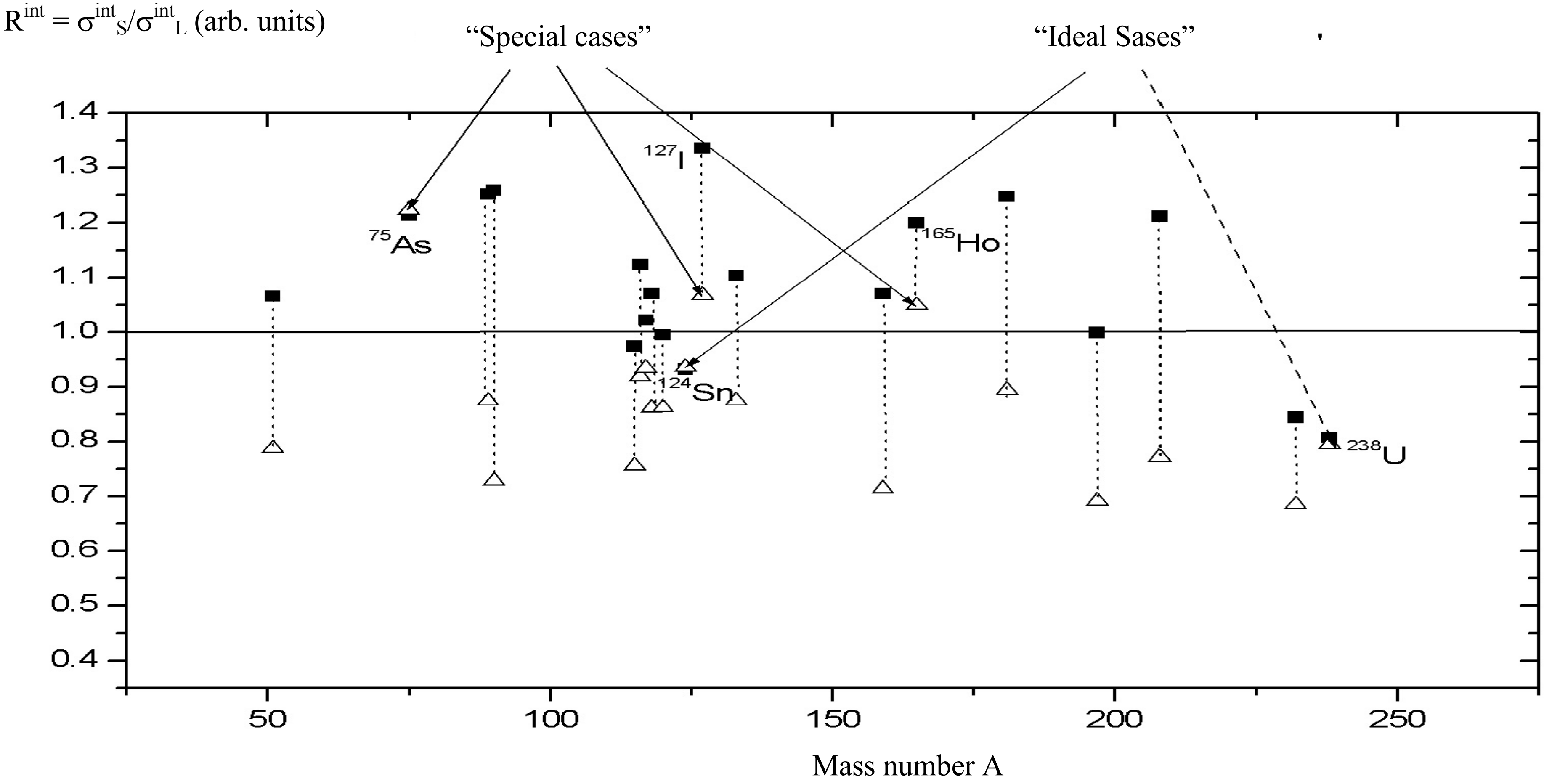
FIGURE 1. Complete R^{int}_{syst} systematic ($\langle R^{int}_{syst} \rangle = 1.12$).

Partial Photoneutron Reactions (γ,n) and (γ,2n)

Beside discrepancies between (γ,xn) cross sections there are certain discrepancies (Table 2) between (γ,n) and (γ,2n) reactions cross section data1). For 12 nuclei (^{89}Y, ^{115}In, ^{117,118,120,124}Sn, ^{133}Cs, ^{159}Tb, ^{165}Ho, ^{181}Ta, ^{197}Au, ^{208}Pb) it was found out9) that as a rule while the integrated (γ,n) reaction cross section from Saclay is higher than that from Livermore, the integrated (γ,2n) reaction cross section is, vise versa, lower. These data were accurately (more precisely calculation of needed energy shifts ΔE and normalizations, some initial data substitutions) recalculated10), added by analogous data for another 7 nuclei (^{51}V, ^{75}As, ^{90}Zr, ^{116}Sn, ^{127}I, ^{232}Th, ^{238}U) and are presented in Table 2. One can easily see that as a rule while integrated (γ,n) reaction cross section from Saclay is higher than that from Livermore, integrated (γ,2n) reaction cross section is, vise versa, lower, both differ from R^{int}(γ,xn).

TABLE 2. Partial (γ,n) and (γ,2n) reactions integrated cross section data (Saclay/Livermore) ratios and $R^{int}(\gamma,xn) = \sigma^{int}{}_{S}(\gamma,xn)/\sigma^{int}{}_{L}(\gamma,xn)$.

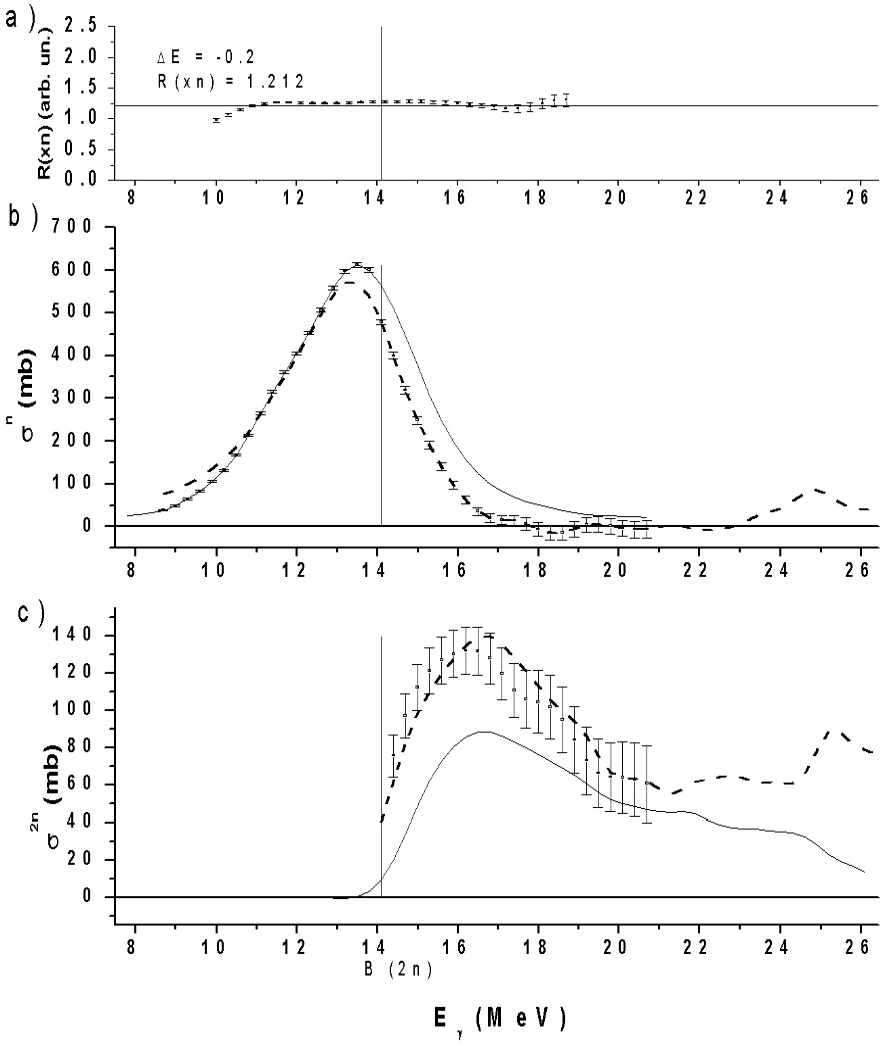
Nucleus	$\sigma^{int}{}_{S}(\gamma,n)/\sigma^{int}{}_{L}(\gamma,n)^{1,9,10)}$ (arb. units)	$\sigma^{int}{}_{S}(\gamma,2n)/\sigma^{int}{}_{S}(\gamma,2n)^{1,9,10)}$ (arb. units)	$R^{int}(\gamma,xn)^{10)}$ (arb. units)
^{51}V			1.066
^{75}As			1.214
^{89}Y	1279/960=1.33	74/99=0.75	1.252
^{90}Zr			1.259
^{115}In	1470/1354=1.09	278/508=0.55	0.974
^{116}Sn			1.103
^{117}Sn	1334/1380=0.97	220/476=0.46	1.022
^{118}Sn	1377/1302=1.06	258/531=0.59	1.071
^{120}Sn	1371/1389=0.98	399/673=0.75	0.995
^{124}Sn	1056/1285=0.82	502/670=0.75	0.932
^{127}I			1.336
^{133}Cs	1828/1475=1.24	328/503=0.65	1.104
^{159}Tb	1936/1413=1.37	605/887=0.68	1.071
^{165}Ho	2090/1735=1.20	766/744=1.03	1.2
^{181}Ta	2180/1300=1.68	790/881=0.90	1.247
^{197}Au	2588/2190=1.18	479/777=0.62	0.999
^{208}Pb	2731/1776=1.54	328/860=0.38	1.212
^{232}Th			0.844
^{238}U			0.762


$R^{int} = \sigma^{int}{}_S/\sigma^{int}{}_L$ (arb. units)
"Special cases"
"Ideal Sases"
^{127}I
^{75}As
^{165}Ho
^{124}Sn
^{238}U
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
50
100
150
200
250
Mass number A

On the base of detailed comparison of (γ,n) and (γ,2n) reactions data with that for (e,n) and (e,2n) obtained for ^{181}Ta using both neutron multiplicity sorting and residual activity measurement methods it was shown[9)] that Saclay neutron multiplicity sorting procedure was incorrect: (γ,2n) data were underestimated (some of those were interpreted as (γ,n) events) and correspondingly that for (γ,n) reaction – overestimated. The method used for correction[9,10)] is very simple and clear. Because (γ,xn) = (γ,n) + 2(γ,2n), ratio $R = \sigma(\gamma,xn)_S/\sigma(\gamma,xn)_L$ must be used for Saclay and Livermore data joint correction. Using that one can obtain expression for Saclay corrected (γ,2n) reaction cross section $\sigma(\gamma,2n)_S^*$

$$R\sigma(\gamma,2n)_L = \sigma(\gamma,2n)_S^* = \sigma(\gamma,2n)_S + ½(\sigma(\gamma,n)_S - R\sigma(\gamma,n)_L). \tag{3}$$

Saclay (γ,n) reaction cross section part $(½(\sigma(\gamma,n)_S - R\sigma(\gamma,n)_L)$ is added ("transmitted back") to Saclay (γ,2n) reaction cross section $\sigma(\gamma,2n)_S$. Saclay (γ,n) reaction cross section is corrected vise versa by subtraction of $R\sigma(\gamma,n)_L$ cross section for energies higher the threshold of reaction (γ,2n). The left part of expression (3) means that recalculated Saclay (γ,2n) reaction cross section $\sigma(\gamma,2n)_S^* = R\sigma(\gamma,2n)$ must be in agreement with Livermore (γ,2n) reaction cross section multiplied by R. As an example Fig. 2 represents the results of joint correction of Saclay and Livermore data for ^{159}Tb - (γ,n) and (γ,2n) reaction cross sections for ^{159}Tb before and after joint correction described.



The results of joint correction of total and partial photoneutron reaction cross sections for ^{208}Pb obtained at Saclay and Livermore:

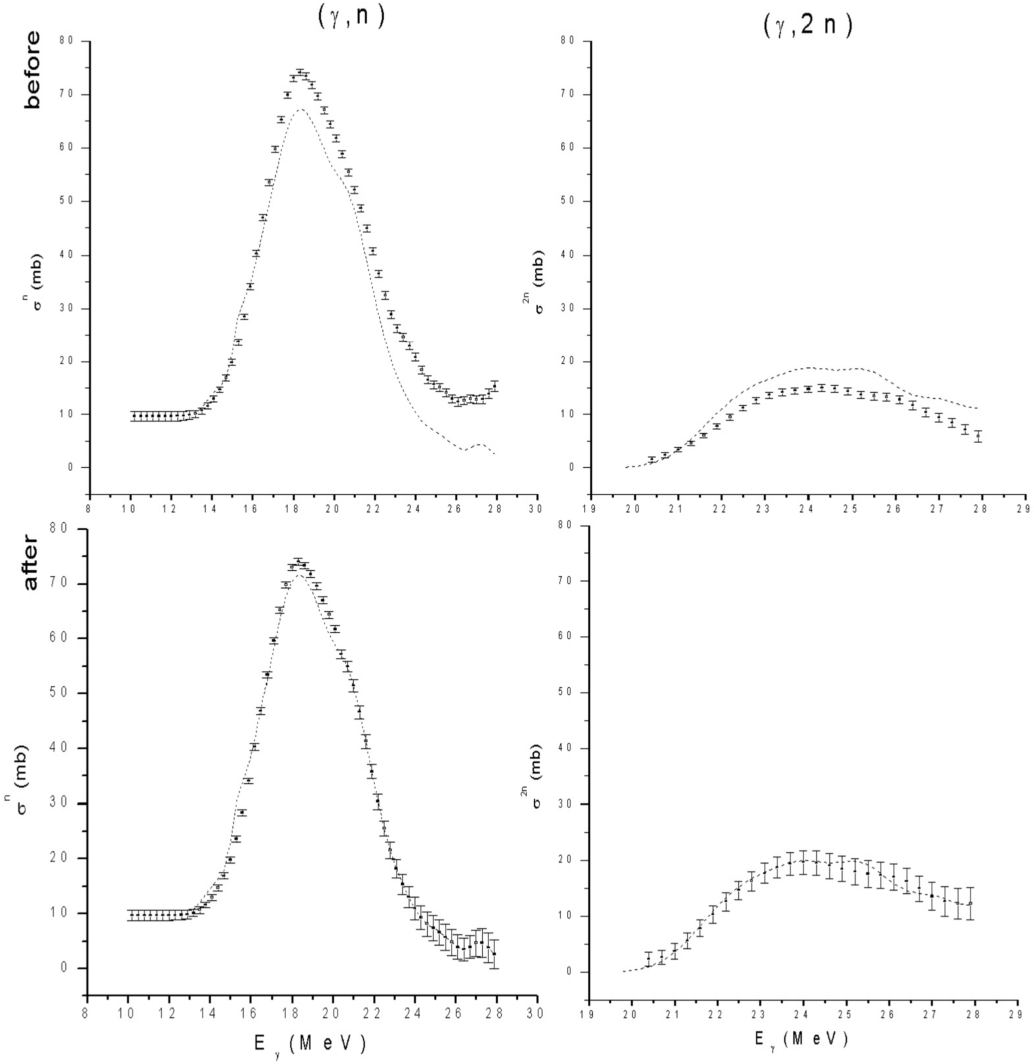
a) ratios R(E) for (γ,xn) reaction cross sections; ΔE and R(xn) are presented;

b) (γ,n) reaction cross section data:

- **solid line– initial Saclay data $\sigma^n{}_S$;**
- **dots with error bars – evaluated Saclay data $\sigma^n{}_S{}^*$;**
- **dotted line – Livermore evaluated data $R\sigma^n{}_L$;**

c) (γ,2n) reaction cross section data:

- **solid line – initial Saclay data $\sigma^{2n}{}_S$;**
- **dots with error bars – evaluated Saclay data $\sigma^{2n}{}_S{}^*$;**
- **dotted line – Livermore evaluated data**



Comparison of ^{51}V Saclay (dots with error bars) and Livermore (dash) data for (γ,n) and (γ,2n) reaction cross sections before and after joint correction described.

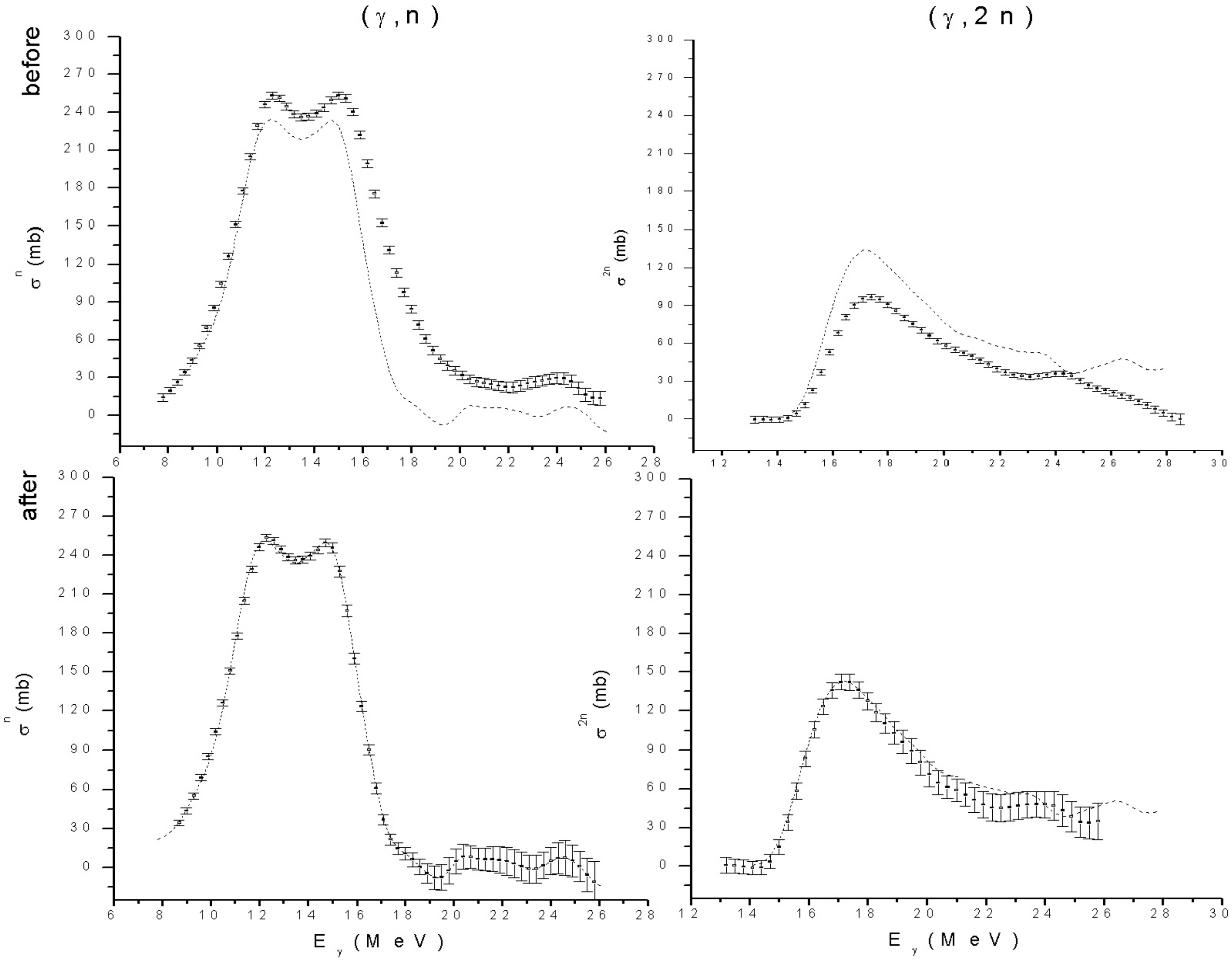


FIGURE 2. Comparison of ^{159}Tb Saclay (error bars) and Livermore (dash) (γ,n) and (γ,2n) reaction cross section data before and after joint correction described.

SUMMARY: MODERN STATUS OF WELL-KNOWN DATA

Things described explain the “modern” status of well-known published photonuclear data: value, accuracy and reliability of each data obtained could be understandable only after analysis of systematical disagreements depended on experimental method used.

Some important conclusions. The “modern” status of data under discussion means:

- significant experiments results discrepancies force one to use data obtained individually: attention must be paid both to experimental method and data processing procedure used in each laboratory;
- (γ,xn) cross sections obtained using QMA-photons at Livermore have in general absolute values smaller then that obtained using both BR- and QMA-photons at other laboratories; therefore (γ,xn) cross sections data of Livermore for 19 nuclei studied[12)] must be corrected - multiplied by appropriate (Table 2) coefficients $R^{int}(\gamma,xn) = R^{int}(\gamma,n) = \sigma^{int}{}_{S}(\gamma,n)/\sigma^{int}{}_{L}(\gamma,n)$; for others – systematic coefficient $<R^{int}{}_{syst}> = 1.12$[8)] could be used at least;
- (γ,n) and $(\gamma,2n)$ reactions cross sections obtained at Saclay because of incorrect neutron multiplicity sorting procedure are not correct and consistent each other and must be recalculated using expression (3);
- Livermore neutron multiplicity sorting procedure is correct and therefore Livermore (γ,n) and $(\gamma,2n)$ cross sections are in consistence with each other and with (γ,xn) cross sections but both can be used only multiplied by $R^{int}(\gamma,xn)$ (Table 2) or $<R^{int}{}_{syst}>$.

Some important physical consequences. Several physical consequences are following, most important are:

- it looks like that E1 GDR decays dominantly statistically: many Saclay interpretations of high-energy tails of (γ,n) reaction cross sections as contributions of high-energy neutrons from GDR nonstatictical direct decay (those contributions evaluated to be about 17 - 30 %) because of small decreasing of (γ,n) reaction cross sections for energies higher than (γ,2n) reaction threshold B(2n) look very doubtful; Saclay (γ,n) reaction cross sections corrections described decrease those and put them into accordance with Livermore data: direct decay contributions are not more than 10 - 12 %;
- large extra integrated cross section σ^{int}(γ,abs) ≈ 1.3 – 1.5 60NZ/A (MeV×mb) became doubtfully being all due to effective mass of nucleon changing because of the effect of exchange forces: the errors in Saclay procedure of neutron multiplicity sorting seriously affect their results for total photoabsorption cross section evaluation using the following reaction cross section data combinations (γ,abs) = (γ,sn) + (γ,p) and (γ,sn) = (γ,xn) - (γ,2n); as it was shown above mistake in (γ,2n) reaction data produces the mistakes in
- both (γ,sn) and (γ,abs) reaction data; correction described do them more smaller.

ACKNOWLEDGMENTS

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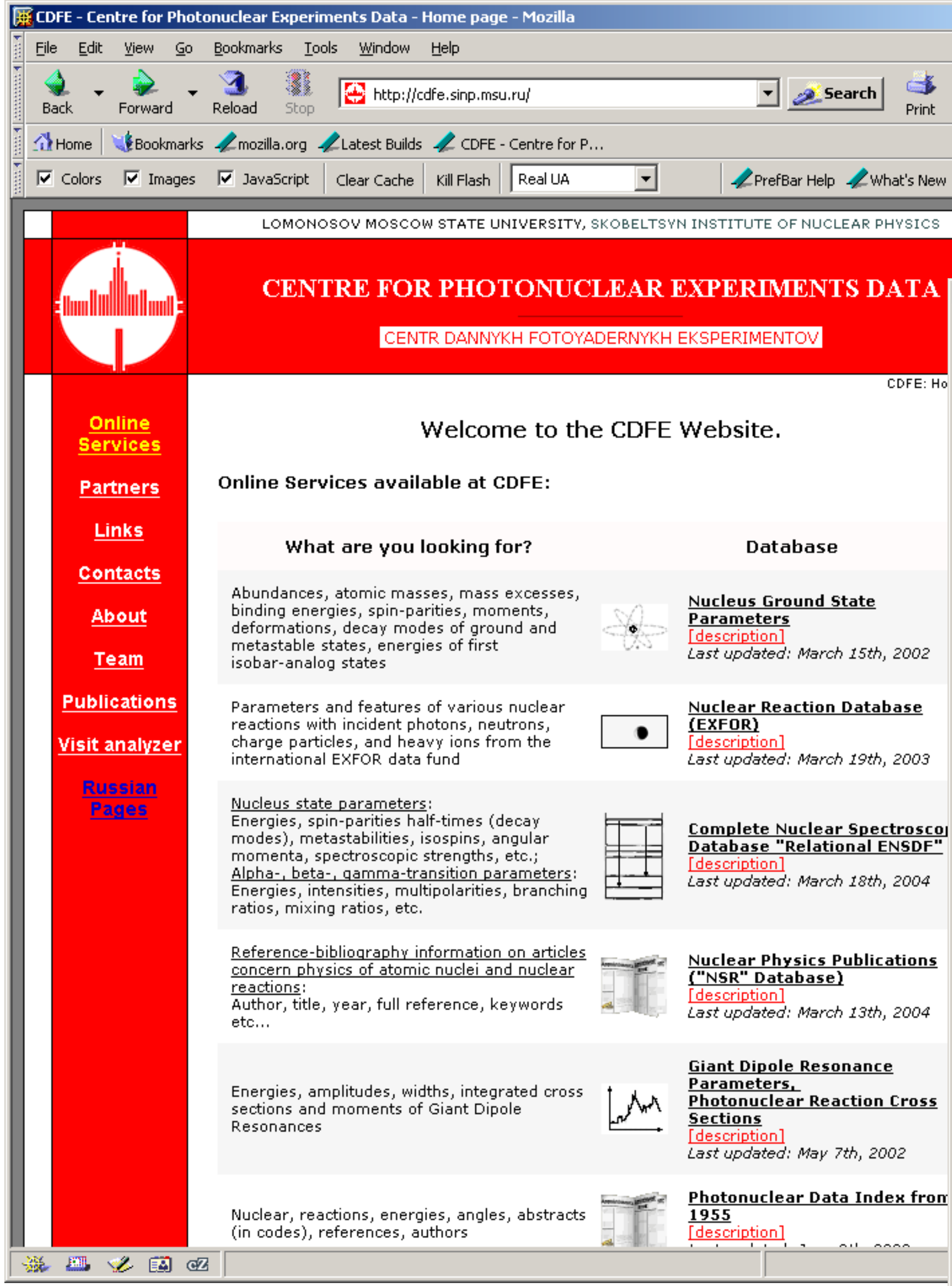

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Parameters and features of various nuclear reactions with incident photons, neutrons, charge particles, and heavy ions from the international EXFOR data fund	**Nuclear Reaction Database (EXFOR)** [description] *Last updated: March 19th, 2003*
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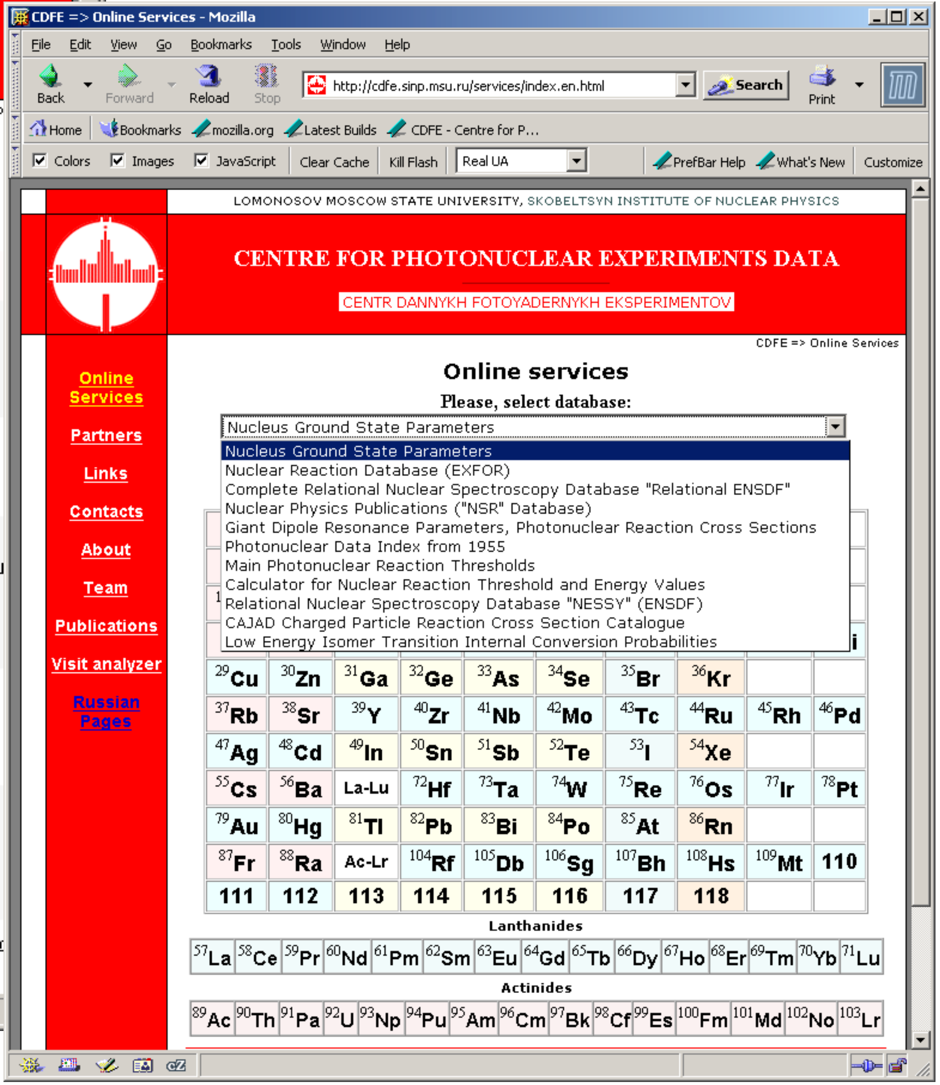
Nuclear, reactions, energies, angles, abstracts (in codes), references, authors	**Photonuclear Data Index from 1955** [description]



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- Relational Nuclear Spectroscopy Database "NESSY" (ENSDF)
- CAJAD Charged Particle Reaction Cross Section Catalogue
- Low Energy Isomer Transition Internal Conversion Probabilities

^{29}Cu	^{30}Zn	^{31}Ga	^{32}Ge	^{33}As	^{34}Se	^{35}Br	^{36}Kr		
^{37}Rb	^{38}Sr	^{39}Y	^{40}Zr	^{41}Nb	^{42}Mo	^{43}Tc	^{44}Ru	^{45}Rh	^{46}Pd
^{47}Ag	^{48}Cd	^{49}In	^{50}Sn	^{51}Sb	^{52}Te	^{53}I	^{54}Xe		
^{55}Cs	^{56}Ba	La-Lu	^{72}Hf	^{73}Ta	^{74}W	^{75}Re	^{76}Os	^{77}Ir	^{78}Pt
^{79}Au	^{80}Hg	^{81}Tl	^{82}Pb	^{83}Bi	^{84}Po	^{85}At	^{86}Rn		
^{87}Fr	^{88}Ra	Ac-Lr	^{104}Rf	^{105}Db	^{106}Sg	^{107}Bh	^{108}Hs	^{109}Mt	110
111	112	113	114	115	116	117	118		

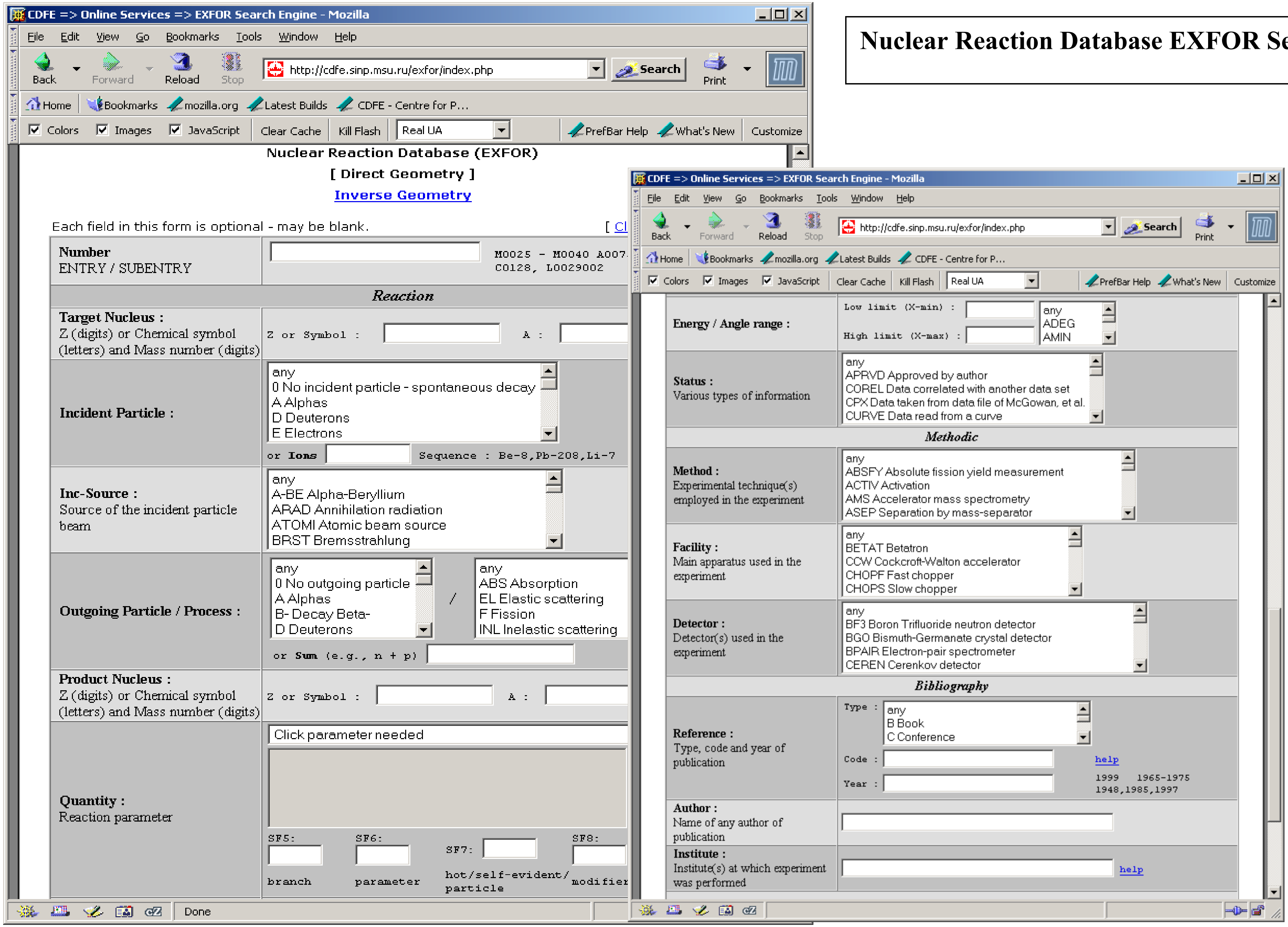
Lanthanides

^{57}La	^{58}Ce	^{59}Pr	^{60}Nd	^{61}Pm	^{62}Sm	^{63}Eu	^{64}Gd	^{65}Tb	^{66}Dy	^{67}Ho	^{68}Er	^{69}Tm	^{70}Yb	^{71}Lu

Actinides

^{89}Ac	^{90}Th	^{91}Pa	^{92}U	^{93}Np	^{94}Pu	^{95}Am	^{96}Cm	^{97}Bk	^{98}Cf	^{99}Es	^{100}Fm	^{101}Md	^{102}No	^{103}Lr

Nuclear Reaction Database EXFOR Search Engine.



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[Direct Geometry]

Inverse Geometry

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Number
ENTRY / SUBENTRY
M0025 - M0040 A007
C0128, L0029002

Reaction

Target Nucleus :
Z (digits) or Chemical symbol (letters) and Mass number (digits)
Z or Symbol : A :

Incident Particle :
any
0 No incident particle - spontaneous decay
A Alphas
D Deuterons
E Electrons
or Ions Sequence : Be-8,Pb-208,Li-7

Inc-Source :
Source of the incident particle beam
any
A-BE Alpha-Beryllium
ARAD Annihilation radiation
ATOMI Atomic beam source
BRST Bremsstrahlung

Outgoing Particle / Process :
any
0 No outgoing particle
A Alphas
B- Decay Beta-
D Deuterons
/
any
ABS Absorption
EL Elastic scattering
F Fission
INL Inelastic scattering
or Sum (e.g., n + p)

Product Nucleus :
Z (digits) or Chemical symbol (letters) and Mass number (digits)
Z or Symbol : A :

Quantity :
Reaction parameter
Click parameter needed
SF5: branch
SF6: parameter
SF7: hot/self-evident/particle
SF8: modifier

Energy / Angle range :
Low limit (X-min) :
High limit (X-max) :
any
ADEG
AMIN

Status :
Various types of information
any
APRVD Approved by author
COREL Data correlated with another data set
CPX Data taken from data file of McGowan, et al.
CURVE Data read from a curve

Methodic

Method :
Experimental technique(s) employed in the experiment
any
ABSFY Absolute fission yield measurement
ACTIV Activation
AMS Accelerator mass spectrometry
ASEP Separation by mass-separator

Facility :
Main apparatus used in the experiment
any
BETAT Betatron
CCW Cockcroft-Walton accelerator
CHOPF Fast chopper
CHOPS Slow chopper

Detector :
Detector(s) used in the experiment
any
BF3 Boron Trifluoride neutron detector
BGO Bismuth-Germanate crystal detector
BPAIR Electron-pair spectrometer
CEREN Cerenkov detector

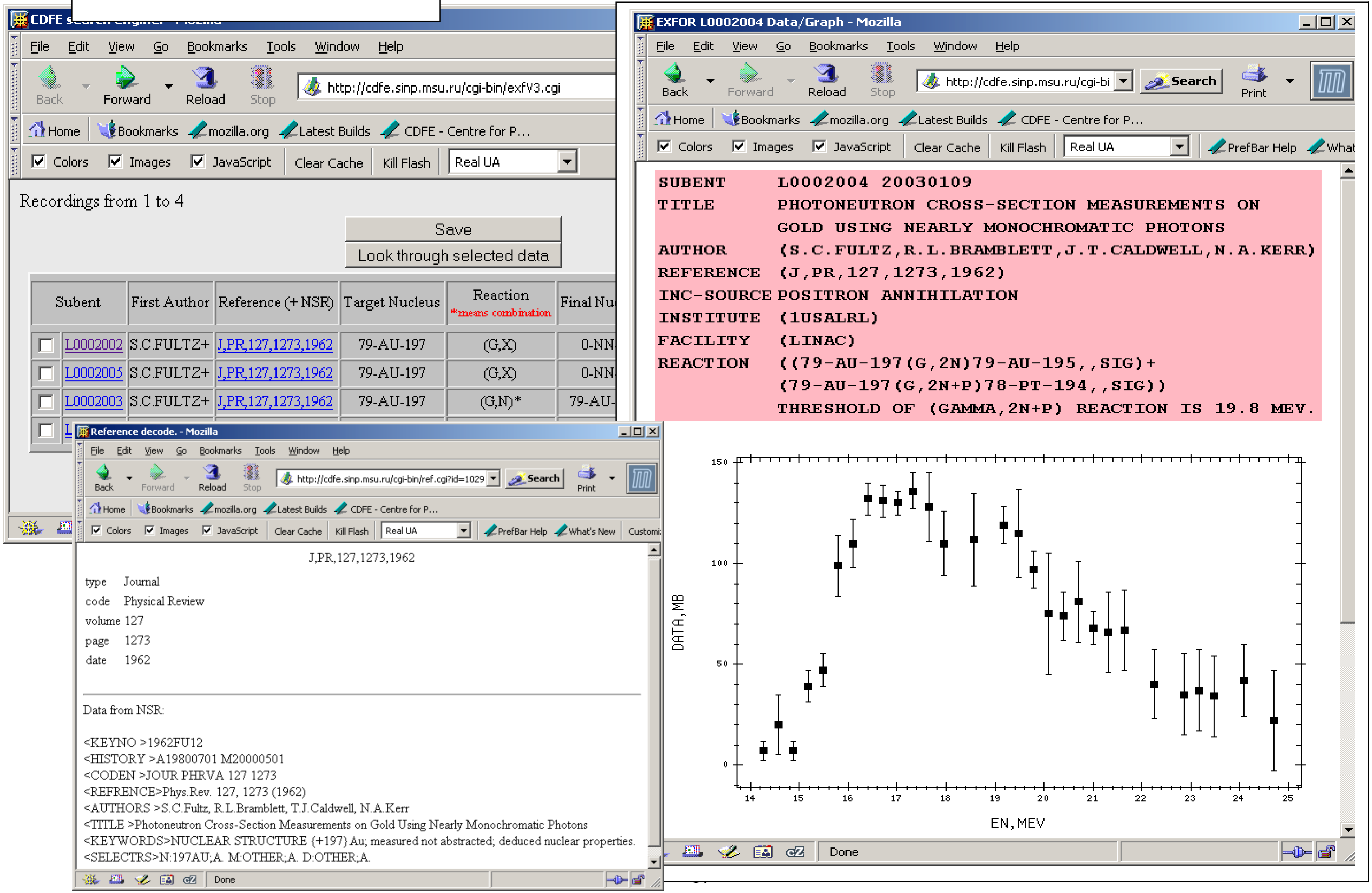
Bibliography

Reference :
Type, code and year of publication
Type : any
B Book
C Conference
Code : help
Year : 1999 1965-1975
1948,1985,1997

Author :
Name of any author of publication

Institute :
Institute(s) at which experiment was performed
help

EXFOR database output.



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☐	L0002005	S.C.FULTZ+	J,PR,127,1273,1962	79-AU-197	(G,X)	0-NN
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☐	L					

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TITLE        PHOTONEUTRON CROSS-SECTION MEASUREMENTS ON
             GOLD USING NEARLY MONOCHROMATIC PHOTONS
AUTHOR       (S.C.FULTZ,R.L.BRAMBLETT,J.T.CALDWELL,N.A.KERR)
REFERENCE    (J,PR,127,1273,1962)
INC-SOURCE   POSITRON ANNIHILATION
INSTITUTE    (1USALRL)
FACILITY     (LINAC)
REACTION     ((79-AU-197(G,2N)79-AU-195,,SIG)+
             (79-AU-197(G,2N+P)78-PT-194,,SIG))
             THRESHOLD OF (GAMMA,2N+P) REACTION IS 19.8 MEV.
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J,PR,127,1273,1962

type Journal
code Physical Review
volume 127
page 1273
date 1962

Data from NSR:

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<REFRENCE>Phys.Rev. 127, 1273 (1962)
<AUTHORS >S.C.Fultz, R.L.Bramblett, T.J.Caldwell, N.A.Kerr
<TITLE >Photoneutron Cross-Section Measurements on Gold Using Nearly Monochromatic Photons
<KEYWORDS>NUCLEAR STRUCTURE {+197} Au; measured not abstracted; deduced nuclear properties.
<SELECTRS>N:197AU;A. M:OTHER;A. D:OTHER;A.
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Yadernaya Fizika (Physics of Atomic Nuclei), to be published, 2004.

Electromagnetic Dissociation of Ultrarelativistic Heavy Ions and Photonuclear Cross Sections in the Giant Resonance Region

V.V.Varlamov[1], B.S.Ishkhanov[2], N.N.Peskov[1], M.E.Stepanov[2], I.A.Pshenichnov[3]

[1]*Skobeltsyn Institute of Nuclear Physics,*
[2]*Physics Faculty, Lomonosov Moscow State University, 119992 Moscow, Russia*
[3]*Instutute for Nuclear Research, Russian Academy of Science, 117312 Moscow, Russia*

Calculations of electromagnetic dissociation cross sections of ultrarelativistic heavy ions are generally based on approximations and extrapolations of the experimental data on photon-induced nuclear reactions. In particular, there exists a proposal to monitor the beam luminosity in ultrarelativistic heavy-ion colliders by measuring neutron emission rates in mutual electromagnetic dissociation of colliding nuclei. The discrepancy between the photonuclear data obtained in different experiments deteriorates the accuracy of the method, which rests on calculated dissociation cross sections. Basing on a systematic analysis of the experimental photoneutron reaction cross sections, the reasons for such discrepancy are investigated, and a means of eliminating the disagreement is proposed. By confronting calculation results with the recent experimental data on electromagnetic dissociation of 30 A GeV ^{208}Pb, it is demonstrated that the obtained evaluated cross sections of (γ,n) and $(\gamma,2n)$ reactions, when used to adjust the model, make possible to improve the reliability of predicted electromagnetic dissociation cross sections.