^{90}Zr GDR Isospin Splitting New Parameters

V.V.Varlamov, N.N.Peskov, M.E.Stepanov

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

Abstract. New data on photoneutron reactions ^{90}Zr(γ,n)^{89}Zr and ^{90}Zr(γ,2n)^{88}Zr cross sections obtained as results of combined joint correction of two experiments carried out with quasimonoenergetic annihilation photons at Livermore (USA) and Saclay (France) were analyzed. An information on ^{90}Zr(γ,p)^{89}Y reaction cross section and on energy positions of states with various values of isospin in ^{90}Zr and neighboring nuclei – members of the correspondent isospin multiplet - were included. New data on ^{90}Zr GDR isospin splitting parameters were obtained on the base of joint analysis of data on GDR states appeared as resonances in photoproton and photoneutron reaction cross sections and possible channels of their decay via final states with various isospin values. In detail study of parameters of giant dipole resonance isospin splitting (for example, for ^{22}Ne, ^{63,65}Cu, ^{58,60,62}Ni, ^{90}Zr ^{208}Pb) it was obtained before that both isospin splitting energy values ΔE and isospin component ratios R are quite different from predictions of traditional model. The reason is that simple geometric model developed mainly for heavy nuclei does not take into account some features of reactions on medium and light nuclei. The point is that in those nuclei: 1) Coulomb barrier is not too high and does not forbid completely $T_<$-states proton decay and 2) Excitation energies of $T_>$-states in (N - 1) nuclei are not enough high and $T_>$-states neutron decay also is not forbidden. Therefore the clear separation ($T_>$ - (γ,p) and $T_<$ - (γ,n)) does not realized – GDR states with different isospins are mixed and could be separated only using special methods. Nevertheless on the whole $T_>$-states primarily forming (γ,p) reaction are lying at higher energies in comparison with $T_<$-states primarily forming (γ,n) reaction. The most interesting result is the specific role of the (γ,2n) reaction. In many cases its absolute cross section value is of the same order as of (γ,p) reaction but its threshold and energy thresholds for excitation of $T_>$-states in (N-2) nuclei are very high also. Therefore because $T_0(N) = T_0(N - 2) + 1$ at the GDR energies two-neutron reaction can occur only through $T_<$-states decay. So the picture of GDR isospin splitting became quite different from simple conception scheme: $T_<$-states dominates at energy ranges of (γ,n) and (γ,2n) reactions, but $T_>$-states between them – at energy range of (γ,p) reaction. Therefore the total GDR width increased but ΔE is not the difference between of (γ,p) and (γ,n) reaction cross section centers of gravity – the contribution of (γ,2n) reaction cross section must be included.

INTRODUCTION

The experimental data for GDR isospin splitting value

$$\Delta E = E_{c.g.}(T_>) - E_{c.g.}(T_<), \quad (1)$$

where $E_{c.g.}$ are the centers of gravity of cross sections $\sigma^>$ and $\sigma^<$ - components of GDR with isospins $T_> = T_0 + 1$ and $T_< = T_0 = (N - Z)/2$ (ground state isospin value) and ratio R of GDR isospin components intensities

$$R = \sigma^>_{-1}/(\sigma^>_{-1} + \sigma^<_{-1}), \quad (2)$$

where $\sigma_{-1} = \int\sigma E^{-1}dE$ is the first moment of the GDR integrated cross section have been analyzed [1] for many nuclei.

For many of those (for example, ^{14}C, ^{44,48}Ca, ^{48,54}Ti, ^{54}Cr, ^{54}Fe, ^{65}Cu, ^{55}Co) clear discrepancies were obtained in comparison of predictions of traditional models [2 – 5] developed for relatively heavy nuclei (A > 90) description

$$\Delta E^{теор} = U(T_0 + 1)/T_0 = U_0(T_0 + 1)/A, \quad (3)$$

where $U = (U_0/A)T_0$, U_0 – nuclear symmetry energy.

For U_0 there are several significantly different estimations. In [4] on the base of coherent GDR effects taking into account for nuclei lighter than Cu the value U_0 = 60 MeV has been obtained, but in [2] for single particle excitations - U_0 = 100 MeV. At the same time in [3] the function $U_0(A)$ has been calculated theoretically – that is decreased from U_0 = 60 MeV for large A to U_0 = 14 MeV for small A.

In [2] the ratio R has been calculated in the frame of simple geometric model

$$R^{theor} = 1/(T_0 + 1). \quad (4)$$

It is clearly seen from (4) that $\sigma^{>}$ -component intensity is smaller than that for $\sigma^{<}$ -component and that the factor is stronger that simple geometric ($1/T_0$) because of $\sigma^{<}$ - $\sigma^{<}$ particle-hole excitations space difference.

In [1] basing on results of analysis of many experimental data that has been shown that discrepancies mentioned reflect the individual character of GDR isospin components behavior in various nuclei. The reasons are the energetic and isospin restrictions for neutron channel decay of isobar-analogue states of nuclei mentioned does not described by the simple geometric models.

The essence of the GDR isospin splitting conception is vell-known. The initial γ–quantum excites in the nucleus with non-zero ground state isospin $T_0 = (N-Z)/2 \neq 0$ two groups of levels with isospins $T_< = T_0$ and $T_> = T_0 + 1$, that are concentrated at different energies - $T_>$-states are placed higher than $T_<$-ones. As a rule the decay of $T_<$-states is permitted for both neutron and proton channels, but it is not in case of $T_>$-states. They are decaying preferentially via protons because neutron decay is frequently forbidden by isospin selection rulles and additionally is restricted by energy balances. Therefore as that has been shown in [13] and in many others the correspondent changing in the character of behavior of energy dependence of $\sigma(\gamma,p)/\sigma(\gamma,n)$ ratio confirms the appearance of many $T_>$-states above the background of $T_<$-ones.

That changing is the foundation of the following method of GDR isospin splitting parameters investigation [6, 13, 15, 16]:

- The energy dependence of $\sigma(\gamma,p)/\sigma(\gamma,n)$ ratio is analyzed with the aim of founding out of the threshold of changing from preliminary constant to clear increasing;
- Both $\sigma(\gamma,p)$ and $\sigma(\gamma,n)$ are approximated by gaussians in such a manner that their parameters at small energies were maximally coincided because both cross sections in that region are connected with the same $T_<$-states decay;
- Using the gaussians parameters parameters of GDR $T_<$-components are obtained for both cross sections at low energies and that of GDR $T_>$-components at high energies;
- The correspondent component center of gravity difference ΔE (1) gives the GDR isospin splitting value and integrated cross section difference – their intensity ratio R (2).

The approximately the same (lorenz lines instead of guauss line) method has been used in [15, 16] for combined analysis of ^{90}Zr photoproton cross section from [15] and photoneutron cross section from [17].

^{90}Zr GDR isospin splitting parameters [15].

Component	$T_<$	$T_>$	ΔE	R
$E^{c.g.}_{.}$ (MeV)	16.7	20.4	3.7	
$\sigma_{(\gamma,n)}$ (mb)	211.0	29.0		0.1
$\sigma_{(\gamma,p)}$ (mb)	23.5	26.0		

The several shortages of estimations carried out are evident:

- The photoneutron cross section of Saclay [17] has been used that must be recalculated because some mistakes in neutron multiplicity obtaining procedure [18 – 22];
- The estimation of the GDR isospin splitting parameters has been carried out using the (γ,p) and (γ,n) reaction cross section data without addition information about (γ,np) and (γ,2n) channels, though the equations (1) and (2) are based on the data not partial reaction cross section but on the data of photoabsorption data;
- The estimation carried out has been based on cross section absolute values but not on integrated cross section values;
- Lorenz line are the better description for one isolated maximum, not for sums of overlapped resonances (the gaussian line is the better approximation).

Therefore this work is devoted to the new evaluation of the ^{90}Zr GDR isospin splitting parameters in conditions free of shortages listed above.

New evaluation has been carried out using the Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics Centre for Photonuclear Experiments Data (CDFE – Centr Dannykh Fotoyadernykh Eksperimentov) Nuclear Reaction Database (EXFOR) - http://cdfe.sinp.msu.ru/exfor/index.php.

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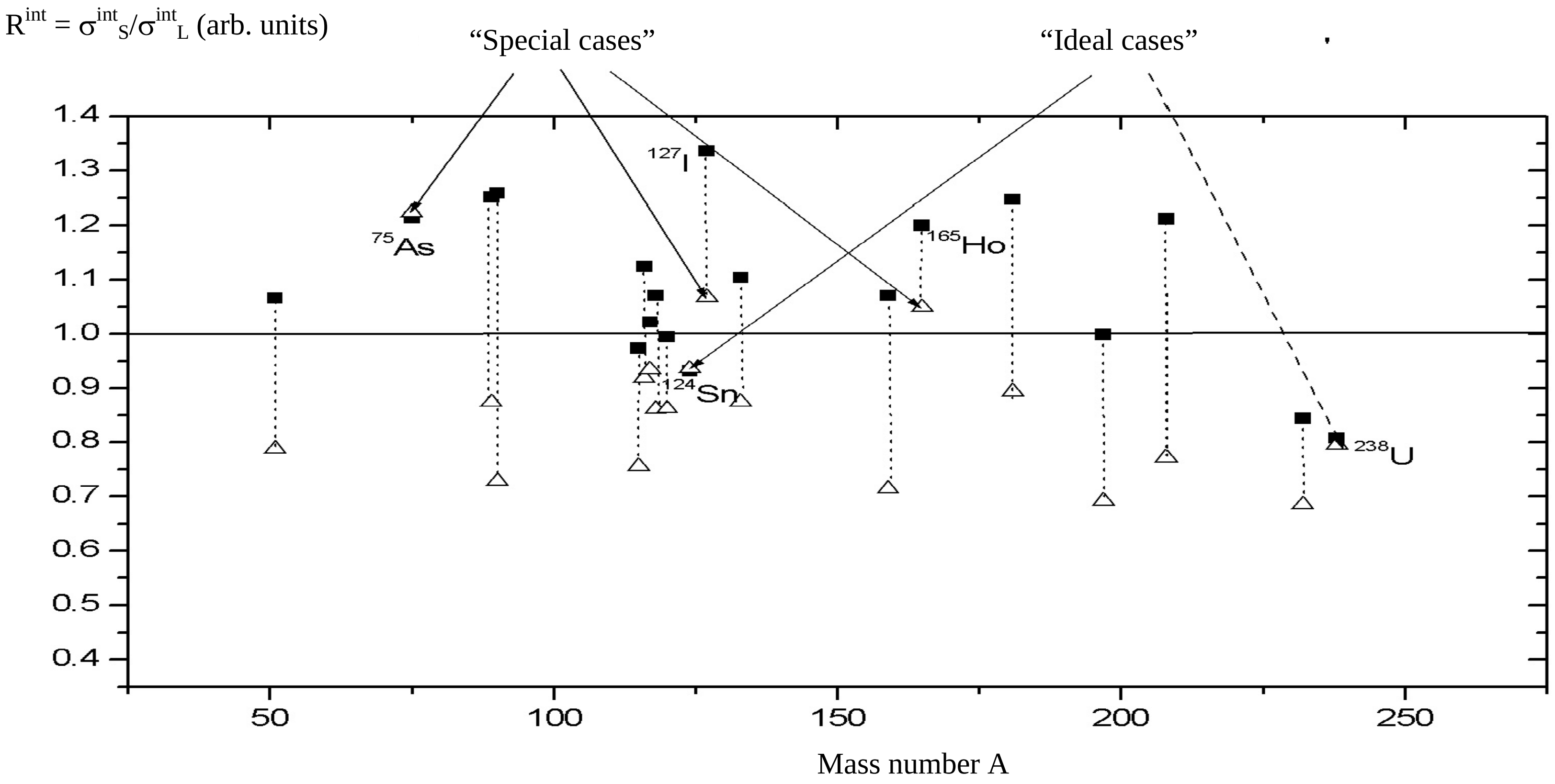
That database [23] has been developed in accordance with recommendation [24] of IAEA Nuclear Data Section in the frame of International IAEA Nuclear Reaction Data Centres Network (http://www-nds.iaea.org/nrdc.html) on the base of international data fund EXFOR and includes many data on the nuclear reactions induced by photons, electrons, neutrons, charge particles and heavy ions. Data from well-known Atlases of photonuclear reaction cross sections [27, 28] and reference - bibliography comprehensive publications [29, 30] are presented also.

SYSTEMATICAL DISAGREEMENTS OF DATA OBTAINED IN PHOTONUCLEAR EXPERIMENTS WITH QUASIMONOENERGETIC ANNIHILATION PHOTONS

The detailed system analysis [18 – 23] of the (γ,xn), (γ,n) and (γ,2n) reaction cross section data obtained using quasimonoenergetic annihilation photon beems at Livermore (USA) and Saclay (France) was carried out for 19 (for 7 of them – at first) 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. It was observed that the (γ,xn) reaction cross section data obtained at both laboratories without using neutron multiplicity sorting procedure disagree by 10 – 15 %. Additionally it was found out that the disagreement of partial reactions (γ,n) and (γ,2n) cross sections, obtained at both laboratories using neutron multiplicity sorting procedure are significantly more (till 30 – 40 %) and as a rule have opposite directions. These disagreements were interpreted as the result of difference of neutron multiplicity sorting procedures used in both laboratories: that is incorrect at Saclay with the result of incorrect transmission of the part of (γ,2n) reaction cross section into that of (γ,n) reaction. The special method was used to move the data into consistence. Its idea is that definite "false" part of (γ,n) reaction cross section was recalculated and transmitted back into that of reaction (γ,2n)

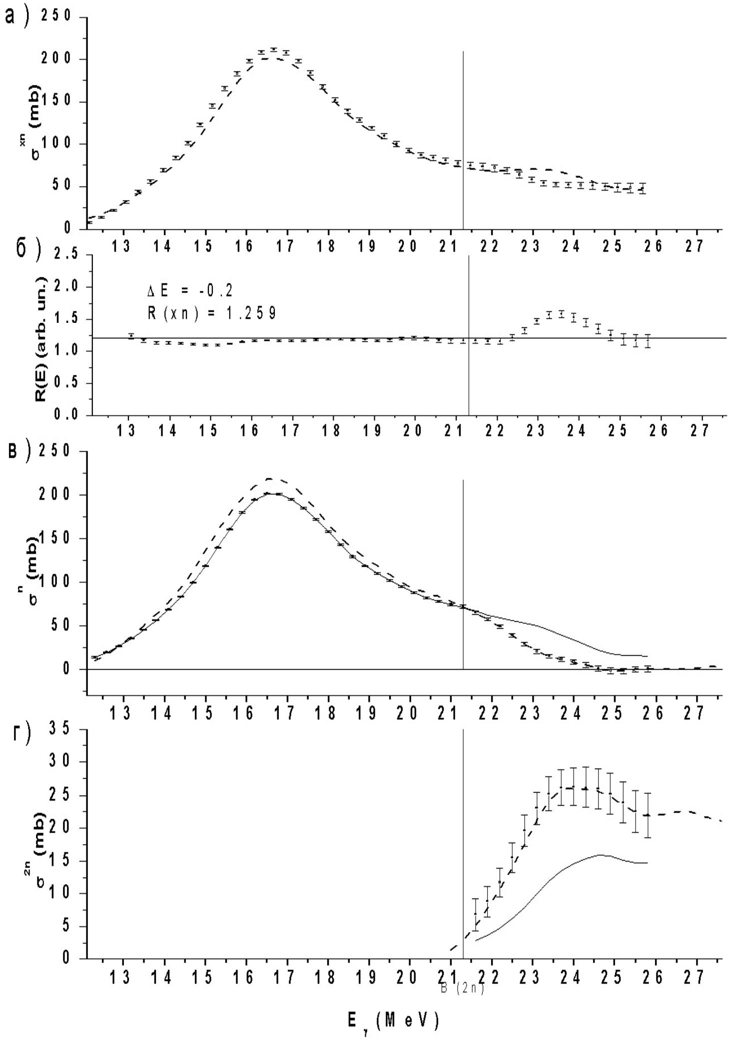


Systematics [22, 23] of values $R^{int}(n) = \sigma^{int}_{Saclay}(\gamma,n)/\sigma^{int}_{Livermore}(\gamma,n)$ – squares and $R^{int}(2n) = \sigma^{int}_{Saclay}(\gamma,2n)/\sigma^{int}_{Livermore}(\gamma,2n)$ – triangles.

"Special cases" - $(\gamma,2n)$ cross section ratios are more than 1.0.

"Ideal cases" - (γ,n) and $(\gamma,2n)$ cross section ratios are near.

"Special cases" and "Ideal cases" were processed individually [22, 23].



The results of joint correction [22, 23] of total and partial photoneutron reaction cross sections for ^{90}Zr 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:

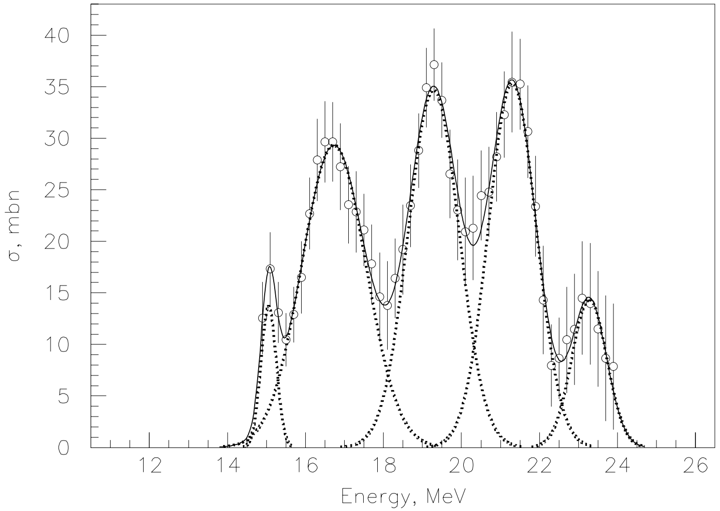
- solid line– initial Saclay data σ^{n}_{S};
- dots with error bars – evaluated Saclay data $\sigma^{n}_{S}{}^{*}$;
- dotted line – Livermore evaluated data Rσ^{n}_{L};

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

- solid line – initial Saclay data σ^{2n}_{S};
- dots with error bars – evaluated Saclay data $\sigma^{2n}_{S}{}^{*}$;
- dotted line – Livermore evaluated data Rσ^{2n}_{L}.

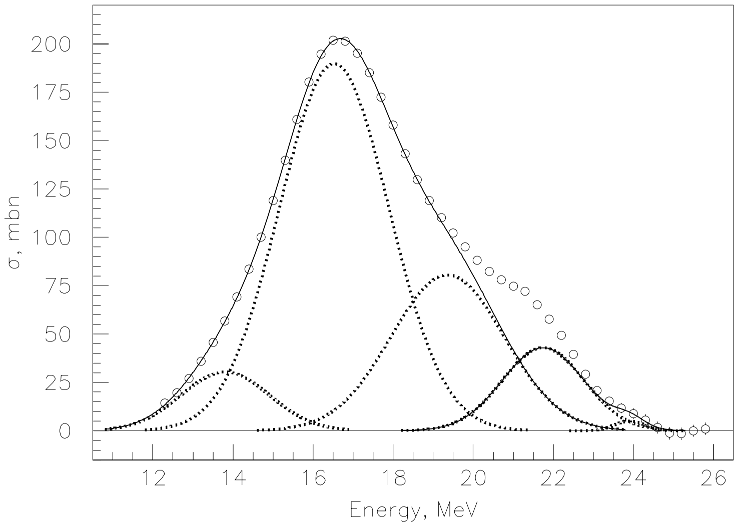
90Zr GDR ISOSPIN SPLITTING PARAMETERS FROM THE PHOTONEUTRON AND PHOTOPROTON REACTIONS CROSS SECTIONS DATA

$^{90}Zr(\gamma,p)^{89}Y$ and $^{90}Zr(\gamma,n)^{89}Zr$ reaction cross section approximation by gaussians



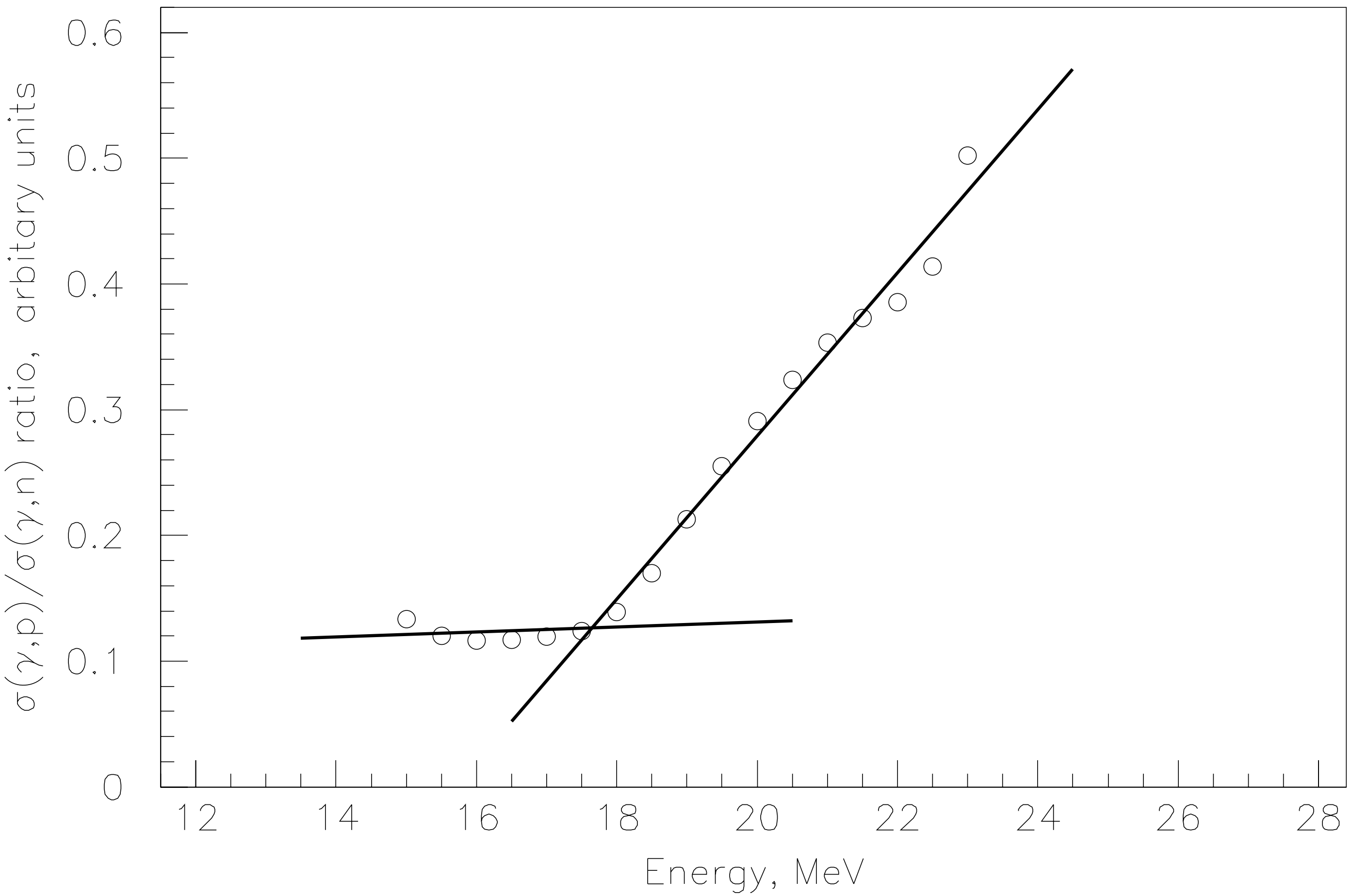
σ_1^{max} = 14. ± 4. мб E_1^{max} = 15.1 ± 0.1 МэВ Γ_1^{Gauss} = 0.2 ± 0.1 МэВ $FWHM_1$ = 0.5 ± 0.2 МэВ	σ_2^{max} = 29.0 ± 2.0 мб E_2^{max} = 16.7 ± 0.1 МэВ Γ_2^{Gauss} = 0.8 ± 0.1 МэВ $FWHM_2$ = 1.9 ± 0.2 МэВ
σ_3^{max} = 35.0 ± 2.0 мб E_3^{max} = 19.3 ± 0.1 МэВ Γ_3^{Gauss} = 0.7 ± 0.1 МэВ $FWHM_3$ = 1.5 ± 0.3 МэВ	σ_4^{max} = 35.0 ± 2.0 мб E_4^{max} = 21.3 ± 0.1 МэВ Γ_4^{Gauss} = 0.6 ± 0.1 МэВ $FWHM_4$ = 1.4 ± 0.2 МэВ
σ_5^{max} = 14.0 ± 4.0 мб E_5^{max} = 23.3 ± 0.1 МэВ Γ_5^{Gauss} = 0.5 ± 0.1 МэВ $FWHM_5$ = 1.1 ± 0.4 МэВ	

$^{90}Zr(\gamma,p)$ reaction cross section [15, 16] approximation via 5 gaussians, $\chi^2 = 0.177$.



σ_1^{max} = 30.0 ± 4.0 мб E_1^{max} = 13.8 ± 0.1 МэВ Γ_1^{Gauss} = 1.1 ± 0.1 МэВ $FWHM_1$ = 2.6 ± 0.2 МэВ	σ_2^{max} = 190.0 ± 1.0 мб E_2^{max} = 16.5 ± 0.1 МэВ Γ_2^{Gauss} = 1.1 ± 0.1 МэВ $FWHM_2$ = 3.2 ± 0.1 МэВ
σ_3^{max} = 81.0 ± 1.0 мб E_3^{max} = 19.4 ± 0.2 МэВ Γ_3^{Gauss} = 1.4 ± 0.1 МэВ $FWHM_3$ = 3.3 ± 0.3 МэВ	σ_4^{max} = 43.0 ± 9.0 мб E_4^{max} = 21.7 ± 0.2 МэВ Γ_4^{Gauss} = 1.0 ± 0.1 МэВ $FWHM_4$ = 2.4 ± 0.2 МэВ
σ_5^{max} = 5.0 ± 2.0 мб E_5^{max} = 23.9 ± 0.2 МэВ Γ_5^{Gauss} = 0.4 ± 0.2 МэВ $FWHM_5$ = 0.9 ± 0.5 МэВ	

$^{90}Zr(\gamma,n)$ reaction cross section [21, 22] approximation via 5 gaussians, $\chi^2 = 0.458$.



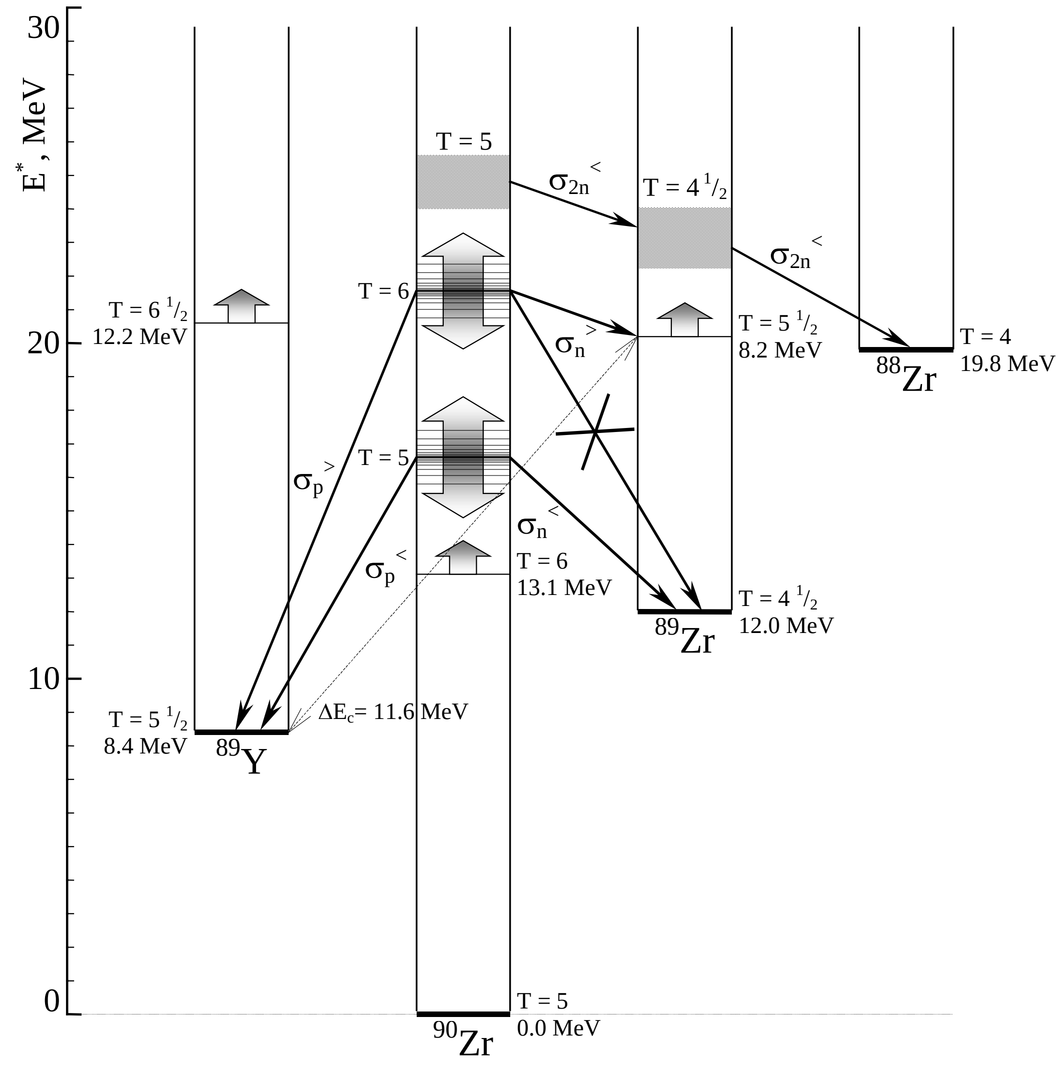
Energy dependence of ^{90}Zr (γ,p) and (γ,n) reactions cross sections ratio r = σ(γ,p)/σ(γ,n).
Both reactions cross sections are smoothed by gaussians with width 2 MeV.

$^{90}Zr(\gamma,p)^{89}Y$, $^{90}Zr(\gamma,n)^{89}Zr$ and $^{90}Zr(\gamma,2n)^{88}Zr$ REACTIONS

ISOSPIN COMPONENTS INTERPRETATION

$^{90}Zr(\gamma,p)^{89}Y$ reaction. Because the character of ratio $r = \sigma(\gamma,p)/\sigma(\gamma,n)$ energy dependence significantly changes at energy 17.7 MeV in accordance with evaluation method described first two maxima in $^{90}Zr(\gamma,p)^{89}Y$ reaction cross reaction at energies 15.1 and 16.7 MeV must be connected primarily with decay of $T_<$-states but the following three maxima at energies 19.3, 21.3 and 23.3 MeV – $T_>$-states.

$^{90}Zr(\gamma,n)^{89}Zr$ reaction. This reaction interpretation could be done by the same manner but with taking into account the additional sircumstance of the energy positions of states with different isospin values in ^{90}Zr and neighboring nuclei. The point is that ^{90}Zr $T_> = 6$ states neutron channel decay is possible only for energies larger than 20.2 MeV [24] – threshold for excitation of the states with isospin $T_> = 5½$ in ^{89}Zr – and their decay into the states with isospin $T_< = 4½$ is forbidden by isospin selection rules. Therefore for photoneutron reaction cross section isospin interpretation is the following: first three maxima at energies 13.8, 16.5 and 19.4 MeV must be connected primarily with the decay of $T_<$-states, but the next two maxima at energies 21.7 and 23.9 MeV - $T_<$-states.



Scheme of excitation and decay processes of different isospin value states of ^{90}Zr and neighboring niclei.

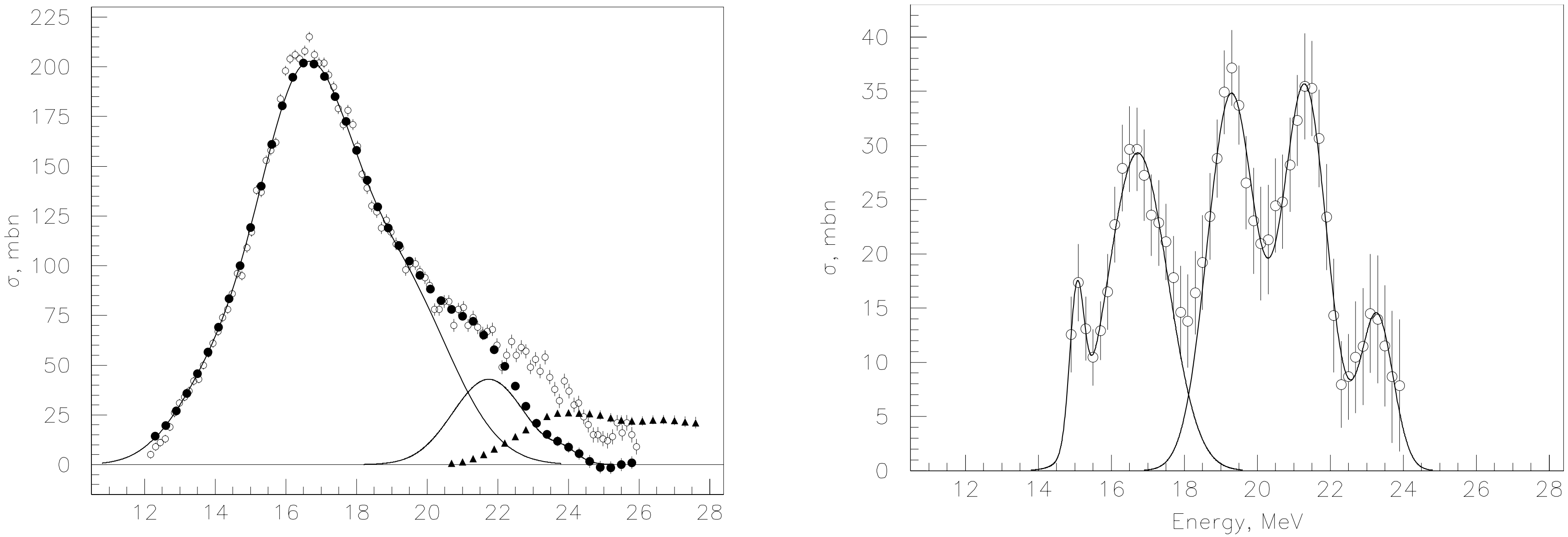
Dotted line – Coulomb energy displacement (ΔE_C = (1.444 · (Z - 1/2) · $A^{-1/3}$ - 1.131) = 11.6 MeV) from ^{89}Zr lowest level with isospin $T_>$ = 5½ to ^{89}Y ground state.

Energy positions [23] of first states with isospins T_0 + 1 are shown by the broad arrows.

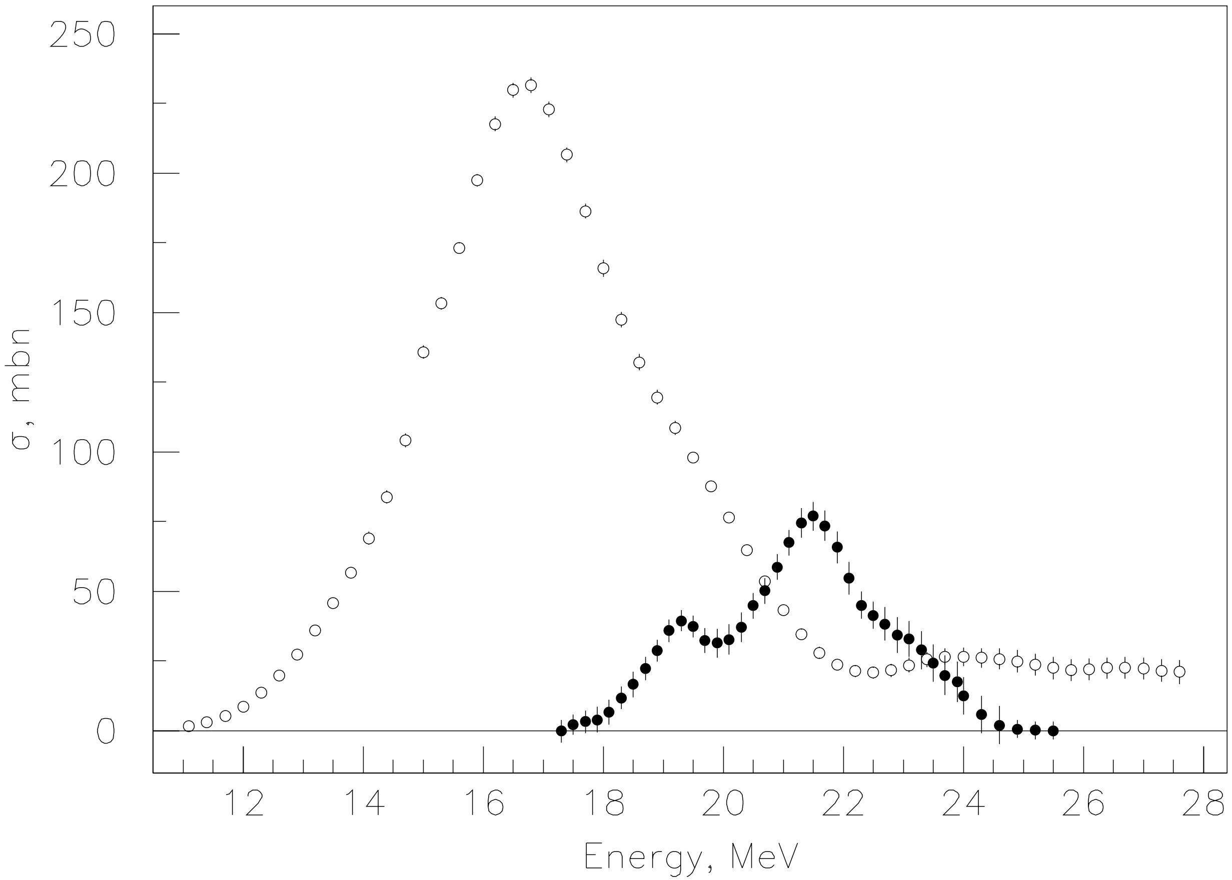
$^{90}Zr(\gamma,2n)^{88}Zr$ reaction. From the scheme presented that is following that ^{90}Zr decay chain for $(\gamma,2n)$ reaction must be ended at ^{88}Zr states with isospin $T_< = 4$ in accordance with isospin selection rules must be connected only with ^{89}Zr states with isospin $T_< = 4½$ and therefore must started only from ^{90}Zr states with isospin $T_< = 5$: the $^{90}Zr(\gamma,2n)^{88}Zr$ reaction cross section is completely connectrd by ^{90}Zr $T_<$-states decay.

$^{90}Zr(\gamma,np)^{88}Y$ reaction. Unfortunately the analogous analysis of that reaction is not possible because the needed information about the appropriate decay chains through the ^{90}Zr states is not available.

All things described above give to one possibility to obtain at first both isospin components of all reaction cross sections under discussion and therefore secondly– new evaluations of ^{90}Zr GDR isospin splitting.



^{90}Zr(γ,n) – left- and ^{90}Zr(γ,p) – right –
reactions cross sections approximations by gaussians.
Curves show correspondent isospin components.



Total photoabsirption reaction $^{90}Zr(\gamma,abs)$ cross section $T_<$- and $T_<$- isospin components.

^{90}Zr GDR isospin components parameters.

Parameters	$T_<$- component	$T_>$- component
Amplitude (mb)	231.0	80.7
Width (MeV)	4.1	3.2
Center og gravity (MeV)	17.9 (1)	21.2 (1)
Range of integration (MeV)	11.1 – 27.6	17.3 – 25.8
Integrated cross section σ^{int} (MeV • mb)	1216.5 (58)	242.3 (70)
First moment $\sigma^{int}{}_{-1}$ (mb)	69.9 (37)	11.48 (32)

^{90}Zr GDR isospin splitting parameters.

Reaction	T	$E^{c.g.}$., MeV	ΔE, MeV	σ^{int}, MeV•mb	σ^{int}/ 1.1 x 60NZ/A	σ^{int}/ 60NZ/A	σ_{-1}, mb	R
(γ,abs)	$T_>$	21.2 (1)	***3.3 (2)***	242.3 (70)	***0.17***	***0.18***	11.6 (3)	***0.14***
	$T_<$	17.9 (1)		1216.5 (58)	***0.83***	***0.92***	69.9 (4)	
(γ,p)	$T_>$	20.6 (1)		126.8 (53)	0.087	0.095	6.2 (3)	
	$T_<$	16.6 (1)		65.7 (33)	0.045	0.049	4.0 (2)	
(γ,n)	$T_>$	21.8 (1)		113.9 (32)	0.078	0.085	5.2 (1)	
	$T_<$	17.1 (1)		1013.4 (22)	0.69	0.760	60.0 (3)	
(γ,2n)	$T_>$	-	-	-	-	-	-	
	$T_<$	24.9 (1)		130.3 (27)	0.09	0.098	5.3 (1)	

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