T-ODD ASYMMETRY EFFECTS OF THE LIGHT PARTICLES EMISSION IN THE HEAVY NUCLEUS TERNARY FISSION BY THE COLD POLARISED NEUTRONS

A.M. Gagarski[1], F. Gonnenwein[2], I.S. Guseva[1], T.A. Zavarukhina[1], Yu.N. Kopatch[3], T.E. Kuzmina[4], M. Mutterer[5], V. Nesvizhevsky[6], G.A. Petrov[1], T. Soldner[6], and G. Tiurin[4]

[1] FSBE "Petersburg Nuclear Physics Institute named B.P. Konstantinov", 188300 Leningrad region, Gatchina, Orlova Roscha, Russia
[2] Universitat Tubingen, Physicalisches Institut, D 72976 Tubingen Germany
[3] Joint Institute for Nuclear Researches,141980 Moscow region, Dubna, Russia
[4] Radium Institute named V.G. Khlopin, 194021 Skt. Petersburg, Russia
[5] Technische Universitat Darmstadt, D 64289 Germany
[6] Laue-Langevin Institute, BR156, 38042 Grenoble, France

1. Introduction

The new physical effect of the T-odd asymmetry of the light charged particle (LCP) emission relative to the light fission fragment direction (with the unit momenta $\mathbf{p_\alpha}$ and $\mathbf{p_f}$) in the ^{233}U ternary fission induced by the cold polarized neutrons (with polarization $\boldsymbol{\sigma_n}$) was observed for the first time by the wide international collaboration at the end of 90-th at the ILL High Flux Reactor in Grenoble /1,2/. It was named "TRI-effect" because of formal similarity to the well known effect of **T**ime **R**eversal **I**nvariance in β-decay /3/.

$$W_{TRI} = 1 + D_{TRI}\cdot\boldsymbol{\sigma_n}\cdot[\mathbf{p_f} \times \mathbf{p_\alpha}] \qquad (1)$$

No essential dependence of the T-odd asymmetry coefficient D_{TRI}·on the angle between the vectors $\mathbf{p_f}$ and $\mathbf{p_\alpha}$ was observed in the first experiments. But with further investigations of the similar effect in the ^{235}U ternary fission and with the increasing of experimental accuracy in the ^{233}U ternary fission the definite and specific dependence of such coefficients has been established /4,5,6/. The observed second type of the T-odd asymmetry effect named "ROT-effect" could be described by the following vector-scalar product:

$$W_{ROT} = 1 + D_{ROT}\cdot\boldsymbol{\sigma_n}\cdot[\mathbf{p_f} \times \mathbf{p_\alpha}]\cdot(\mathbf{p_f}\cdot\mathbf{p_\alpha}) \qquad (2)$$

In this equation (2) the coefficient D_{ROT} represents the angle of the LCP angular distribution shift.

To account for these effects the quasi-classical model of the polarized fissioning system rotation about its polarization direction has been proposed by the authors for the first time, /5,6,7,8/. Such a model seems to be rather natural if one takes into account that the even-even compound fissioning system formed after the cold polarized neutron capture has mainly collective types of excitations above the barrier top (including rotation ones). The directions of such rotation and the start velocity have to be completely defined by the compound state spins and their projections on the system symmetry axis. With the assumption that this symmetry axis is conserved along whole way of the system decent from the barrier top to the rupture point, the rotation speed has to be progressively reduced as the inertia momentum is increased with the nucleus elongation up to the rupture.

As a result of the system rotation the trajectories of the resulting charged fission products will be affected in the motion in its relative Coulomb field. In its turn such trajectory changing after fissioning system rupture may give rise to a small turn (or shift) of the LCP angular distribution, compared to the angular distribution without the system rotation. In a general sense the ROT-effect can be considered as a first direct exhibition of the polarized nucleus rotation.

By now detailed investigations of both T-odd asymmetry effects have been performed only for the $^{233,235}U$, ^{239}Pu and partly for the ^{245}Cm ternary fission induced by the cold polarized neutrons. Therewith, all obtained experimental results for the TRI and ROT-effects are successfully described in the frameworks of our semi-classical model of rotation /8/.
In principle, since the T-odd asymmetry effects discovery for the LCP it was evident that similar effects can exist for the neutrons and γ-rays emitted near the rupture time. Nevertheless, the first experiments in the $^{233,235}U$ binary fission did not lead to these effects observation /9,10/.

However, already collected information allowed to conclude that the new T-odd asymmetry effects are closely connected with low energy fission dynamics and its further investigations may open absolutely new ways for the studies of the fission dynamics.

After discovery of the TRI and ROT-effects of the LCP emission asymmetry and its first detailed investigations a number of theoretical publications appeared with the attempts to find acceptable explanations of these two effects in low energy fission. First of all it was done in the framework of the statistical model /11/, then within pure quantum mechanical approach /12/ and, recently, in the approach of spin-orbital interaction /13/. In two first cases the authors left room for possibility to use quasi-classical model for the T-odd asymmetry effect explanation but underlined the necessity to take into account different interference effects between neighbouring nuclear levels. The author of the third publication doesn't need any rotation of the system to explain the T-odd asymmetry effects. However, neither of the three theoretical works gives any ways to perform numerical analysis of the experimental data and the more so to get any estimations of expected values of parameters of new planned experiments.

2. The main experimental results of the TRI and ROT-effects investigations in ternary fission

All results of the TRI and ROT-effects investigations were obtained with the use of the same experimental set-up. Being placed at the polarized neutron beam of ILL High Flux Reactor this set-up makes possible to measure simultaneously energies and angular distributions of the LCPs and fission fragments emitted from the thin targets of fissile nuclei.

Normalized differences of the LCP emission probabilities for two mutually opposite directions of the cold neutron polarizations as a function of the angle between LCP and the light fragments emission directions (ROT-effect) are presented in the Figs 1,2 and 3.

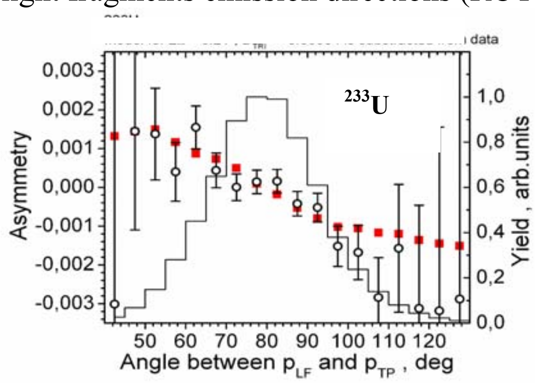

Fig.1. ROT-effect in ^{233}U ternary fission

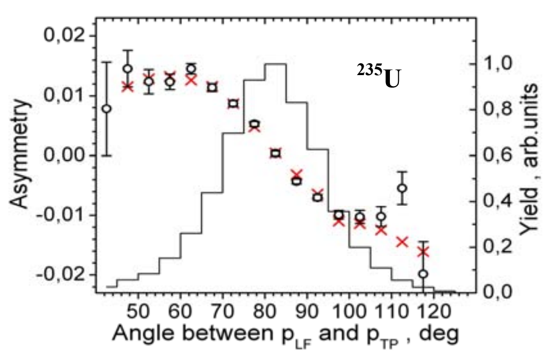

Fig.2. ROT effect in ^{235}Pu ternary fission

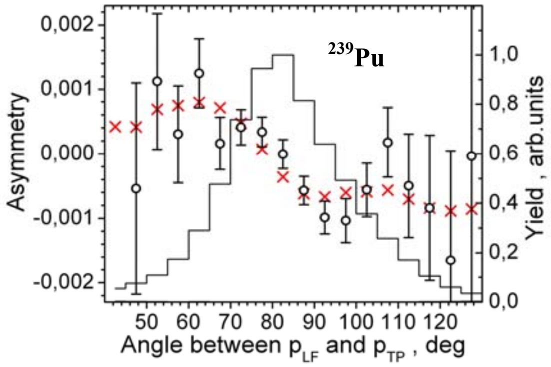

Fig. 3. ROT-effect in ^{239}Pu ternary fission

Target	spin	ROT^0	TRI 10^{-3}
^{233}U	$2^+, 3^+$	0.03(1)	-3.9(1)
^{235}U	$3^-, 4^-$	0.215(5)	1.7(2)
^{239}Pu	$0^+, 1^+$	0.020(3)	0.023(9)
^{245}Cm	$3^+, 4^+$		1.2(1)*

Table I. TRI and ROT effects values for all investigated fissile heavy nuclei

In these cases the part of information that has no angular dependence (TRI-effect) has been subtracted. The LCP angular distributions are shown as the histograms, the points with the error bars are experimental asymmetries of the LCP emission and the calculated asymmetry values are shown by the crosses. The deviations of the experimental and calculated points from the smooth behavior (especially for the case of ^{239}Pu fission) in the region ($90^0 \div 120^0$) may be connected with registration of some admixture of the heavy mass fragments because of relatively bad experimental mass resolution.

Separate values of the TRI and ROT-effects for the ^{233,235}U and ^{239}Pu ternary fission are presented in the Table I. In the case of the ^{245}Cm ternary fission only the sum of both T-odd asymmetry effects has been measured up to now.

3. Comparison of the results of model calculations with the experimental data

The rotation model analyses of the TRI and ROT effects are based on the trajectory calculations of the LCP emission with taking into account the rotation of the polarized fissioning system about the polarization axis. To estimate the influence of the system rotation on the fragments and LCP trajectories in the Coulomb field one needs to know the angular velocity of the system and the start position of the charged fission products just near the rupture point. The angular velocity of a strongly deformed fissioning system just near the rupture point is obtained with the following main assumptions:

1. After the cold polarized neutron absorption the resulting excited compound nucleus is brought above the fission barrier with the spins of the transition states $J^{\pm} = (I \pm ½)$. The ratio of these states occupancies $s = \sigma(I - ½)/\sigma(I + ½)$ can be obtained from the nuclear data analysis.
2. The resulting polarization of these transition states is conserved up to the fissioning system rupture and is defined by the following equations:
   $P(J^+)=(2I + 3)/[3(2I + 1)]\cdot p_n$ for $J^+=(I + ½)$ and $P(J^-)= -1/3\cdot p_n$ for $J^- =(I - ½)$ (3)
   where p_n is the cold neutron polarization. The resulting polarized compound nucleus will undergo rotation around the polarization axis with the angular velocity ω:

$$\omega_{+/-}(J,K)=\begin{cases}\dfrac{J(J+1)-K^2}{J}\cdot\dfrac{\hbar}{2\Im}\cdot p_n & for \quad J=I+1/2\\ -\dfrac{J(J+1)-K^2}{(J+1)}\cdot\dfrac{\hbar}{2\Im}\cdot p_n & for \quad J=I-1/2\end{cases} \tag{4}$$

where K is J projection on the fission symmetry axis, which is conserved the whole fission process, and $\Im$ is the moment of inertia, which constantly increases during the descent from the fission barrier to the rupture point.

If the fission process is going through several transition states, then to obtain the effective angular velocity one needs to perform the following summation:

$$\omega(J)=\sum_K \left|a_K^J\right|^2\omega(J,K), \tag{5}$$

where $\left|a_K^J\right|^2$ - probability of the (J, K) state existence.

3. Fissioning system configuration just before the rupture time was chosen in such a way that all energy and angular distributions of fission products well known from experiments would be well described. /7/

With such assumptions the first estimates of the LCP angular distribution shifts were obtained /8/.

In contrast to the ROT-effects of T-odd asymmetry the TRI-effect has no such a visual interpretation. In principle some factors may have an influence on the probability of the LCP-emission relative to the plane of fission fragments and LCP emission direction such as: a character of vibration excitations on the way to the rupture and the peculiarities of the fissioning system rupture into the fragments and LCP. As a result, it is evident that some supplementary forces may have an effect on the LCPs in addition to the Coulomb and nuclear ones, as for example: Coriolis, centrifugal, and inertial (catapult) forces, connected with successive decreasing of the rotation velocity. It is important to note here that these forces depend on the rotation velocity, starting positions, and linear velocities of the fission fragments and LCPs:

$$\mathbf{F_{Cori}} = -2m\,[\mathbf{v}\times\boldsymbol{\omega}] \qquad \mathbf{F_{centr}} = m\boldsymbol{\omega}\times[\mathbf{r}\times\boldsymbol{\omega}] \qquad \mathbf{F_{catap}} = \mathbf{m}\,[\mathbf{r}\times \mathbf{d}\boldsymbol{\omega}/dt] \tag{6}$$

As both T-odd asymmetry effects appear together and are closely connected with fissioning system rotation it seemed to be reasonable to try to find the way of their joined description in the frameworks of our model. To do so both observed T-odd asymmetry effects were presented as the following sum:

$$D_{ROT}^{TRI}=D_{ROT}+D_{TRI}=A\cdot\left[\omega^+\frac{1}{1+s}+\omega^-\frac{s}{1+s}\right]+B\cdot\left[K^+\omega^+\frac{1}{1+s}+K^-\omega^-\frac{s}{1+s}\right] \tag{7}$$

where $s = \sigma(J^+)/\sigma(J^-)$ is the ratio of fission probabilities through the transition states with the spins $J^{\pm}$, $\omega^{\pm}$ - the proper angular velocities, calculated with the formulas (4), and A, B – the constants. These constants were found from the fit of expression (7) to the experimental data for the TRI and ROT-effects in the ^{235}U ternary fission, where the measurements were performed with the best accuracy.

The empirical expression obtained in such a way was used then for the calculations of the T-odd asymmetry effects in the ^{233}U and ^{239}Pu ternary fission. Tables II - IV show the calculated T-odd effects for different combinations of the K_+ and K_- values with the s-values (ratio of J+

and J- cross sections) and the experimental values of D_{exp} shown in table captions. The value which is the closest to the experimental one is shown in **bold**.

Tables II, III, IV. Calculated values of the ROT-effects (left side) and TRI-effects (right side) in the ternary fission of $^{233,235}U$ and ^{239}Pu

^{233}U ROT (^{0}). $\sigma(J=2)/\sigma(J=3)=0.79$ /14/
$D_{exp} = 0.03(1)^0$

	$K_+=0$	$K_+=1$	$K_+=2$
$K_-=0$	0.118	0.102	**0.053**
$K_-=1$	0.131	0.115	0.066
$K_-=2$	0.170	0.153	0.105

^{233}U TRI-эффект (x 10^{-3})
$D_{exp} = -3.9 \cdot 10^{-3}$

	$K_+=0$	$K_+=1$	$K_+=2$
$K_-=0$	0	-2.4	**-3.5**
$K_-=1$	0.861	-1.5	--2.6
$K_-=2$	0.69	-1.7	-2.8

^{235}U ROT (^{0}). $\sigma(J=3)/\sigma(J=4)= 0.57$ /15/
$D_{exp} = 0.215(1)^0$

	$K_+=0$	$K_+=1$	$K_+=2$	$K_+=3$
$K_-=0$	0.183	0.169	0.128	0.058
$K_-=1$	0.191	0.177	0.135	0.066
$K_-=2$	**0.215**	0.201	0.159	0.090

^{235}U TRI-эффект (x 10^{-3})
$D_{exp} = 1.7 \cdot 10^{-3}$

	$K_+=0$	$K_+=1$	$K_+=2$	$K_+=3$
$K_-=0$	0	-3.5	-6.0	-6.1
$K_-=1$	1.2	-2.4	-4.8	-5.0
$K_-=2$	**1.7**	-1.8	-4.3	-4.4

^{239}Pu ROT (^{0}). $\sigma=0/\sigma(J=1)=2.09$/15/
$D_{exp} = 0.020(3)^0$

	$K_+=0$	$K_+=1$
$K_-=0$	0.057	**0.028**

^{239}Pu TRI-эффект (x 10^{-3})
$D_{exp} = - 0.23 \cdot 10^{-3}$

	$K_+=0$	$K_+=1$
$K_-=0$	0	**-0.38**

As one can see, it is possible to explain successfully all experimental data using equation (7) both in values and in signs. Moreover, the most probable calculated values of the TRI and ROT-effects in the ^{233}U and ^{239}Pu ternary fission very well coincide with experimental ones. This fact, on the one hand corroborates the main assumptions of our semi-classical model and on the other hand permits to predict the expected T-odd asymmetry effects in the new planned experiments in the ^{241}Pu and ^{245}Cm ternary fission.

It is well known that the transition state spins of the $^{242}Pu^*$ and $^{246}Cm^*$ formed after cold neutron capture coincide in values with the corresponding spins of $^{234}U^*$ and $^{236}U^*$. Then, if one assumes that the TRI and ROT effects in the $^{242}Pu^*$ and $^{246}Cm^*$ ternary fission exist at the similar J,K combination as in the $^{234}U^*$ and $^{236}U^*$ one can expect their signs and values given in the bold type (see Tables V and VI).

Tables V and VI. Expected values of ROT and TRI-effects in the ^{245}Cm and ^{241}Pu fission

^{245}Cm ROT (^{0}). $\sigma(J=3)/\sigma(J=4)=$ 5,7 /15/

	$K_+=0$	$K_+=1$	$K_+=2$	$K_+=3$	
$K_-=0$	-0.156	-0.159	-0.169	-0.185	
$K_-=1$	-0.138	-0.141	-0.150	-0.166	
$K_-=2$	**-0.083**	-0.086	-0.095	-0.111	
$K_-=3$	0.009	0.006	-0.004	-0.020	

^{241}Pu ROT (^{0}). $\sigma(J=2)/\sigma(J=3)=0.15$ /15/

	$K_+=0$	$K_+=1$	$K_+=2$	$K_+=3$
$K_-=0$	0.277	0.252	**0.177**	0.052
$K_-=1$	0.280	0.255	0.181	0.056
$K_-=2$	0.292	0.267	0.192	0.067

^{245}Cm TRI (x 10^{-3})

	$K_+=0$	$K_+=1$	$K_+=2$	$K_+=3$	
$K_-=0$	0	-0.829	-1.396	-1.440	
$K_-=1$	2.751	1.923	1.355	1.312	
$K_-=2$	**4.002**	3.173	2.606	2.562	
$K_-=3$	2.251	1.422	0.855	0.812	

^{241}Pu TRI-эффект (x 10^{-3})

	$K_+=0$	$K_+=1$	$K_+=2$	$K_+=3$
$K_-=0$	0	-3.746	5.448	-3.065
$K_-=1$	0.256	-3.490	-5.193	-2.809
$K_-=2$	**0.205**	-3.541	-5.244	-2.860

The simultaneous description of both, TRI and ROT effects by the same combination of the K+/K- values for each measured nucleus, including the predicted ones for $^{242}Pu^*$ and $^{246}Cm^*$, will be very convincing argument in the support of our rotation model of the T-odd asymmetry effects of the LCP-emission in the ternary fission of heavy polarized nuclei.

4. Main results of the search for T-odd asymmetry effects of the γ-rays and neutron emission in the binary fission of polarized nuclei

As it was pointed out in introduction, just after the first observation of TRI-effect of the LCP emission in ternary fission it was evident that similar effects should exist in the processes of the neutrons and γ-quanta radiation if they are emitted near the rupture point. But these effects in the $^{233,235}U$ binary fission have not been observed in the first experiments /9, 10/ up to the level of accuracy about $5\cdot10^{-5}$. And only in 2009 in the work /16/ the ROT-effect of T-odd asymmetry was observed for the γ-quanta radiation in the ^{235}U binary fission and was considered by the authors as an evidence of the prompt γ-quanta emitted near the rupture time. Our subsequent work /17/ corroborated this observation. However, quite different explanation of the observed effect has been proposed. Following the work of Strutinsky /18/ and the mention of Novitsky /16/ we are convinced that this effect is the direct consequence of the appearance in the rupture process of a strongly deformed fissioning system of large angular momenta of the fission fragments. These momenta, which are normally oriented relative to the fission fragment axis of symmetry, are conserved up to the time of the γ-quanta emission ($\geq 10^{-14}$ sec) and lead to the well known angular anisotropy of the γ-quanta emission and the T-odd asymmetry effects:

$$W(\theta')=1+A\cdot\cos^2\theta'+D_{ROT}(\theta')\cdot\left(\sigma_n\left[\mathbf{p}^f\mathbf{p}^\gamma\right]\right) \quad (8)$$

This expression after some simple transformations will lead to the following formula for the T-odd asymmetry coefficient value:

$$D^{\exp}{}_{ROT} \cong -A\cdot\delta\cdot\sin(2\theta')/[1+A\cdot\cos^2(\theta')] \quad (9)$$

where δ is the shift of the γ-quanta angular distribution, θ' – the angle of the γ-quanta emission, and A – angular anisotropy value. The value of δ obtained in our work /17/ was equal to 0.103^0, whichis not too far from the angle of the LCP angular distribution shift in the ternary fission of the same nucleus ^{235}U.

It is necessary to point out that in spite of relatively simple and quite understandable mechanism of the γ-quanta ROT-effect appearance in the binary fission it is undoubtfully closely connected with fissioning system rotation. Namely because of these circumstances the future investigations of this effect in comparison with similar effect for the LCP in ternary fission may be very fruitful for the fission dynamics study at the low excitation energies.

The question about existence of the ROT-effect for the fission neutrons and its energy dependence has been theoretically investigated in details in the work /19/. The main results of this work together with the recent results of its experimental investigations /20/ are shown in Figure 4.

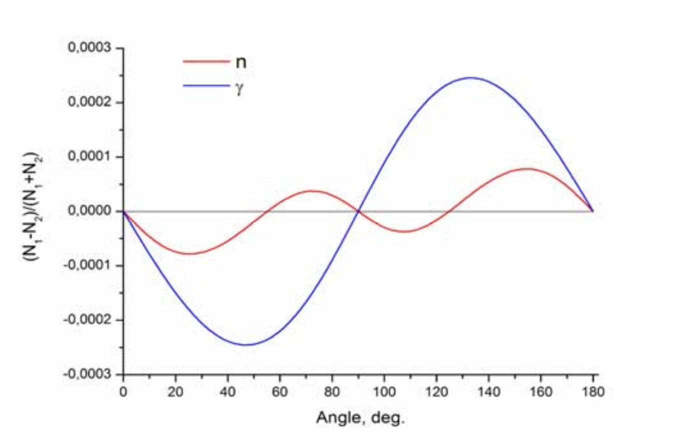

Fig.4. Experimental ROT-effects for neutrons /20/ (black squares) in comparison with theoretical angular dependence of the ROT effects for neutrons and γ-quanta /19/

With regard to the first observation of the ROT-effect of the neutron emission asymmetry the following remarks have to be pointed out. First of all the definite physical effect evidently exists in the ^{235}U binary fission induced by the cold polarized neutrons. However the sign and value of the observed effect turn out to be in the contrast with the theoretical predictions /19/.

But if the difference in signs may be explained by another choice of the vectors order in the formula (2), it is difficult to find the reason for the two times larger size of the effect. It suggests an idea to propose that some instrumental asymmetry could exist during the measurements or the experimental result presented in the Fig.4 includes some value of the TRI-effect of the T-odd asymmetry of neutron emission. In principle TRI-effect value about $1.5\cdot10^{-4}$ would not contradict to the upper limit of this effect existence ($< 6\cdot10^{-5}$) obtained by the same authors in the work /9/.

On the other side complete absence of the TRI-effect for the neutron emission or its relatively small magnitude gives evidence of absolutely different mechanism of neutron emission in fission, as compared to the LCP. The angular distribution of so called "scission" neutrons has to be much less pronounced compared to the LCP one. In addition, the yield of "scission" neutrons accompanied the ^{235}U binary fission is not higher than $(3\div5)\cdot10^{-2}$ /21/, which is much smaller than the average of 2.5 prompt neutrons emitted from the excited fission fragments.

All aforesaid supports the necessity of new more detailed investigations of the TRI and ROT-effects of T-odd asymmetry for neutrons and γ-quanta radiation in comparison with similar effects in ternary fission with the LCP-emission.

References

1. P.Jesinger, G. Daninyan, A. Gagarski et al. Phys. Atom. Nucl.v. 62, (1999)1608.
2. P. Jesinger, A. Kotzle, A. Gagarski, F. Goennenwein et al. NIM A440, 2000, p. 618.
3. K. Schreckenbach et al.In "Time Invariance and Parity Violation in Neutron Reactions" Singapore, World Scientific, 1994, p. 187.
4. A. Gagarski, G. Petrov, F. Goenenwein et al. Proc. Inter. Sem. ISINN-12, JINR 2004, p. 255.

5. A. Gagarski, I. Guseva, F. Goennenwein, G. Petrov et al, Proc. Inter. Sem. ISINN-14, JINR, 2007, p. 93.
6. F. Goennenwein, M. Mutterer, A. Gagarski, I. Guseva,. Phys. Lett. B 652, (2007) 13.
7. I. Guseva and Yu. Gusev. Proc. Intern. Sem. ISINN-14, JINR, 2007, p.101.
8. A. Gagarski, F. Goennenwein, I. Guseva et al. Proc. Int. Sem. ISINN-17, JINR, 2010, p.17.
9. G. Danilyan, V. Krakhotin, V. Pavlov et al.JETP Pis'ma v. 72 (2000)859.
10. V. Sokolov, A, Gagarski, G, Petrov et al. Proc. Inter. Sem. ISINN-12, JINR 2004, p. 25.
11. V. Bunakov and G. Petrov. Proc. Intern. Sem. ISINN-8, JINR, 2000, p.100.
12. V. Bunakov and S. Kadmensky. Proc. Intern. Sem. ISINN-15, JINR, 2008, p.256.
13. A. Barabanov. Proc. Intern. Sem. ISINN-19, JINR, 2011 (to be published). Abstracts p. 20.
14. Yu. Kopath, A. Popov, V.Furman et al. Phys. At, Nucl, v.62, 1999, 840.
15. V. Maslov et al. JENDL, ENDF/B6
16. G. Danilyan, I. Klenke, V. Krakhotin et al. Nucl.Phys. (rus) v.72 (2009)1872.
17. G. Val'ski, A. Gagarski, I. Guseva et al. Izv. RAS (ser. fiz.) v.74 (2010)793.
18. V. Strutinsky. JETF v.37 (1959)861.
19. I. Guseva. Proc. Intern. Sem. ISINN-18, JINR, 2010, p.84.
20. G. Danilyan, I. Klenke, V. Krakhotin et al.Nucl.Phys. (rus)v.73 (2010) p.1155. Abstracts of Intern. Sem. ISINN-19, JINR, 2011, p.24.
21. G. Petrov, A. Vorobiev, V. Sokolov et al. Proc.of 4-th Inter. Workshop on Nuclear Fission and Fission Product spectroscopy. AIP, New York, v. 1175, 2009, p. 289.