DETAILED STUDY OF THE EFFECTS FOLLOWING FROM ROTATION OF THE SCISSIONING NUCLEI IN TERNARY FISSION OF ^{235}U BY COLD POLARISED NEUTRONS (“ROT” AND “TRI” EFFECTS)

A.Gagarski [a], G. Petrov [a], I. Guseva [a], T. Zavarukhina [a],
F. Gönnenwein [b], M. Mutterer [c], J. von Kalben [c], W. Trzaska [d], M. Sillanpää [d],
Yu. Kopatch [e], G. Tiourine [f], T. Soldner [g], V. Nesvizhevsky [g]

[a)] PNPI RAS Gatchina, Russia; [b)] University of Tübingen, Germany;
[c)] Technical University Darmstadt, Germany;
[d)] University of Jyväskylä, Finland; [f)] KRI, St. Petersburg, Russia;
[e)] Frank Laboratory, JINR, Dubna, Russia; [g)] ILL, Grenoble, France

1. Introduction

Since 1998 angular correlations in ternary nuclear fission induced by polarised neutrons at thermal energies were intensively studying by our collaboration. Recently reactions have been of particular interest where the neutron beam hitting the target is polarised longitudinally and the detectors for fragments and ternary particles are mounted in a plane perpendicular to the neutron beam. The angular distribution for one of the fission fragments (FF) and ternary particles (TP) at given neutron spin (σ) can be written as:

$$W(p_{FF}, p_{TP}) \sim (1 + D \cdot \sigma \cdot [p_{FF} \times p_{TP}]) \cdot W_0(p_{FF}, p_{TP}) \qquad (1)$$

with $W_0(p_{FF}, p_{TP})$ – the basic conventional correlation being independent of neutron spin between the momenta of FF and TP; p_{FF}, p_{TP} – momentum of one of the FFs (usually the light FF is taken as a reference) and the TP; σ – neutron spin; and D – coefficient measuring the size of the triple correlation $\sigma \cdot [p_{FF} \times p_{TP}]$.

In experiments with ^{233}U and ^{235}U as the targets it was observed that the angular distribution of ternary particles relative to the momentum of the light fragment (LF), being roughly Gaussian, exhibits a slight variation at the relative level ~ 10^{-3} upon flipping the neutron spin relative to the plane (p_{FF}, p_{TP}) formed by LF and TP momentums [1,3]. It was proposed to distinguish between two types of change of the TP angular distribution when flipping neutron spin. One type is “SCALING” where with spin flip the shape and the position of the angular distribution remains unchanged, but the total probability for TPs to move towards one or the other hemisphere of the (σ, p_{LF})-plane becomes asymmetric. We call this the TRI effect. The second type of change is “SHIFT” when with spin flipping the angular distribution is shifted in angular position without changing the total probability in hemispheres. This is called the ROT effect. In the terms of the formula (1) the TRI effect corresponds to the case when *D* coefficient is constant over angle. While the ROT effect will obviously give rise to a pronounced angular dependence of *D* on the angle between LF and TP.

The ROT effect is traced to a collective rotation of the partially polarized fissioning nucleus around its polarization direction during the acceleration phase of TPs. This hypothesis was corroborated by trajectory calculations [2]. One can suppose that the TRI effect could be due to the rotation affecting other degrees of freedom in the nucleus before rupture. At this stage the inertia forces arising in the rotating scissioning system “break” axial symmetry in the neck region and can help the “latent” TPs to “decide” to which hemisphere they will be emit-

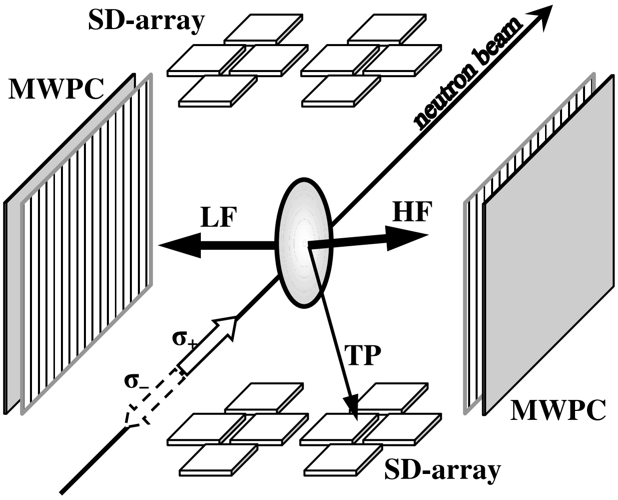

Fig. 1. Sketch of layout of experiment.

ted. The effect of rotation at this stage will not depend on the TP emission angle relative to the LF, because the specific TPs angular distribution is not yet settled.

As follows from the previous experiments, in ^{233}U(n,f) the TRI effect is dominant, while in ^{235}U(n,f) the ROT effect is better pronounced.

For the new experiment performed in 2007 it was suggested to analyze more thoroughly the angular asymmetry (1) in a dedicated study of the reaction ^{235}U(n,f). From the experimental side it was mandatory to improve on the angular resolution for the detection of fission fragments and TPs. By measuring the dependence of the asymmetry coefficient over angle between LF and TP with better resolution it should become feasible to differentiate reliably both TRI effect, which does not depend on TP angle, and the ROT effect whose essence is its angular dependence. (In the work [3], where the ROT effect was discovered, the asymmetry was measured only for two angles 68° and 112° with poor angular resolution determined by the detectors sizes ~50°)

2. Experiment

The experiment was performed on the cold polarized neutron beam PF1 (intensity ~ 10^9 n/s·cm^2 and polarization ~95%) of the Institute Laue-Langevin (Grenoble).

The general scheme of the setup was similar to one we had in all our previous experiments. It is shown in Fig. 1. The neutrons were polarized along the beam axis. The fissile target with diameter of the active spot ~8 cm is located at the centre of the assembly and oriented nearly parallel to the beam axis. Approximately 5 mg of ^{235}U (uranium tetra fluoride) were evaporated as a thin layer of ~100 μg/cm^2 on a thin titanium foil (~100 μg/cm^2) transparent to the FFs. Low-pressure position sensitive multi-wire proportional counters (MWPC) are used for registration of FFs. They are mounted a distance ~12 cm apart from the target plane and serve as stop detectors for the FFs. The size of the MWPCs is ~14×14 cm^2. Two arrays of surface barrier silicon detectors (SD) with 8 diodes each are placed ~ 12 cm away from the target for registration of the TPs at the axis perpendicular to MWPCs. The SD arrays are covered by ~25 μm aluminium foil against damaging by FFs. The target and all detectors assembly are placed in a ~40 litres chamber filled with ~10 mbar of CF_4 counting gas for MWPC operation.

In these experiments one should, as a minimum request, achieve an identification of 'light' and 'heavy' FFs. It can be readily done relying on momentum conservation and measuring times-of-flight of two complementary FFs. In the time-of-flight method the start time mark was provided by the TP detector arrays and stop signals for coincident FFs were derived from the MWPCs. The time resolution was ~1 ns. The two measured FFs times should be corrected for the TP flight time from the target to the detector, which can be found from the measured TP energies (E_{TP}) and the distance from the fission point to the diodes having been hit. The fission position on the target is determined quite accurately by using the coordinates of FFs from the position sensitive MWPCs to reconstruct the fission axis. Knowing coordinates, tim-

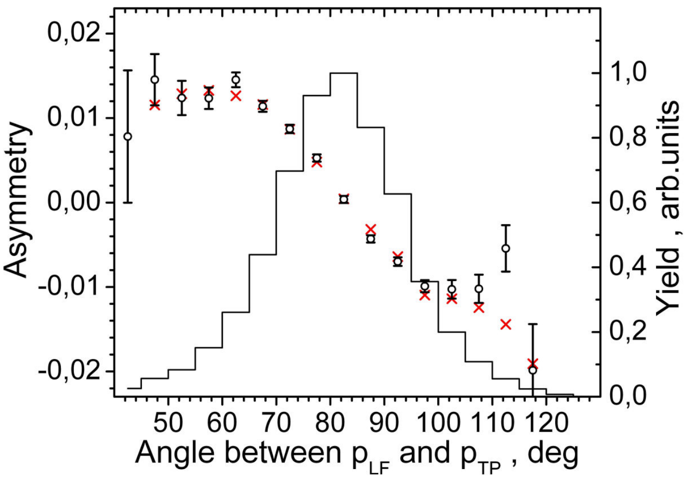

Fig. 2. Angular dependence of the experimental asymmetry for the reaction ^{235}U(n,f) – open points, left scale; angular distribution of TP emission – histogram, right scale; results of ROT+TRI model fit for the asymmetry – crosses. For details see the text.

ing and E_{TP}, all angles between vectors together with the mass of the light fragment (M_{LF}) and the total FFs kinetic energies (E_{FF}) are calculated event-by-event in the off-line analysis. The estimated resolutions for the LF mass are ΔM_{LF} ~8 a.m.u and for the FFs energy ΔE_{FF} ~30 MeV. The coordinate information from the MWPCs together with granulation of the silicon diodes arrays provides angular resolution ~10°.

The experimental value of the asymmetry is defined as follows:

$$A_i = \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}, \qquad (2)$$

where $N_i^{+/-}$ are count rates of the LCP–FF coincidences. The index i means different selection criteria on recorded parameters of the fission event, such as angles, E_{TP}, M_{LF}, E_{FF} and others, while (+/–) indicates the direction of the neutron spin being flipped periodically (~1 Hz) by a spin flipper device. It is easily shown, that the experimental asymmetry A is proportional to D, the proportionality factor in A ~ D accounting for experimental factors such as neutron polarization, accidental background, solid angles of registration etc.

The dependence of the experimental asymmetry A in eq. (2) on the angle between LF and TP is presented in Fig. 2 (open dots). The data are corrected for finite neutron polarization, background of accidental coincidences and geometrical efficiency. The corrected angular distribution of TPs is shown on the same figure as a histogram. The experimental asymmetry as a function of angle ϑ between LF and TP was fitted with a model function constructed on the basis of the hypothesis that, in the general case, the asymmetry is the sum of ROT and TRI effects:

$$A(\vartheta) = S_{ROT} \cdot \left(\frac{Y'(\vartheta)}{2 \cdot Y(\vartheta)} \right) + D_{TRI} \;, \qquad (3)$$

In this formula $Y(\vartheta)$ is the experimental (averaged over two spins) angular distribution and $Y'(\vartheta)$ its derivative. The first and second term on the RHS in (3) corresponds to the ROT and TRI asymmetry, respectively. Obviously, the ROT asymmetry originating from angular shifts depends on the shape of the angular distribution $Y(\vartheta)$ and it is proportional to the normalized derivative $Y'(\vartheta)/Y(\vartheta)$. The TRI asymmetry is constant over angle. The asymmetry is then described with two free parameters: S_{ROT} – the angular shift between TP distributions for the two spin polarizations and D_{TRI} – the relative difference in total probabilities for TPs emitted towards the upper (lower) hemisphere for the two spin directions.

In Fig. 2 the results of the fit based on eq. (3) are indicated by crosses. Evidently the ansatz in eq. (3) describes the experiment very well. The values obtained for the fitting parameters are

$$S_{ROT} = 0.215^\circ \pm 0.005^\circ \text{ and } D_{TRI} = (+1.7 \pm 0.2) \times 10^{-3}.$$

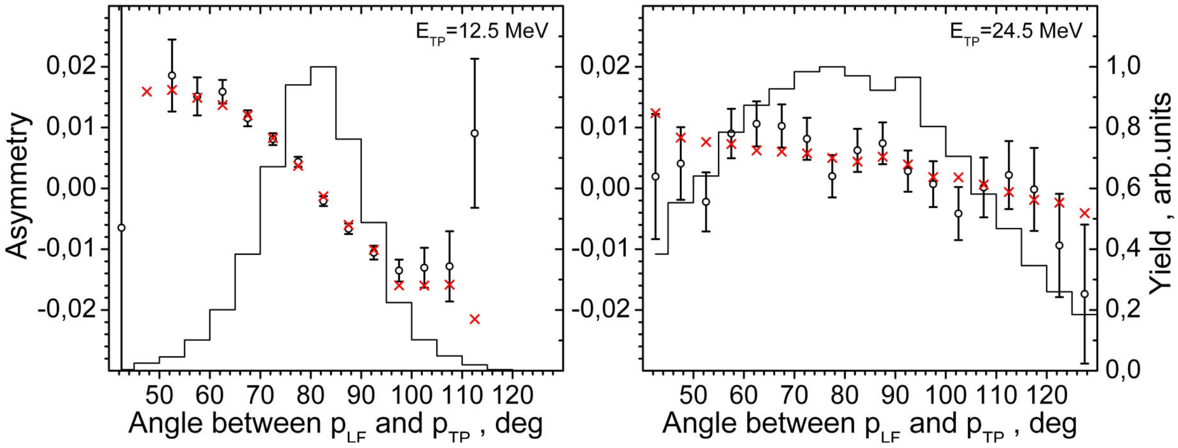

Fig. 3. Angular dependences of the experimental asymmetry and the fit results for two slices on E_{TP}: 12.5±1.5 MeV and 24.5±1.5 MeV. Designations are the same as on the Fig.2. For comments see the text.

For a more detailed study of the asymmetries the ternary events were sorted into bins of selected fission products parameters such as: E_{TP}, M_{LF} (as a fraction of the compound nuclear mass), and E_{FF}. The binned data were evaluated following the same procedure as described above. In spite of the fact that the angular distributions of TPs vary strongly with the energies of TPs and the masses and energies of FFs, the results of the fits were always satisfactory. On Fig. 3 the results of the fits for two bins of E_{TP} , 12.5±1.5 MeV and 24.5±1.5 MeV, with narrow and wide angular distributions respectively, are shown as an example.

In the way described the ROT shifts and TRI coefficients were obtained separately as a function of the above fission observables. In Fig.4 the values obtained for the fitting parameters S_{ROT} and D_{TRI} are plotted versus E_{TP}, M_{LF} and E_{FF}.

For the ROT effect our semi-classical model [3] was verified by comparing the new detailed experimental data with results of trajectory calculations of alpha particle emission from rotating fissioning nuclei. To estimate the effective rotational momentum of the compound system, the ratio $\sigma(J=4^-)$ / $\sigma(J=3^-)$ of the cold neutron capture cross-sections was taken to be 1.8, according to [5]. In a first approach only two fission channels (J,K) = (4,0) and (J,K) = (3,2) were taken into account. The results of trajectory calculation are shown by squares in Fig. 4 [2]. One can see, that the calculations not only reproduce very well the experimental average value of ROT effect, but also the calculated dependencies of the ROT shift on measured parameters agree, at least qualitatively, with the experimental trends.

For the TRI asymmetries, however, we still have no theoretical model which is capable to give quantitative predictions and the experimental data are still a challenge for interpretation.

3. Conclusion

The main conclusion of the present experiment is that at the present level of experimental accuracy we can describe the changes of angular distributions of TPs relative to the LF for opposite spin polarizations of the compound nucleus by only two parameters: the angular shift S_{ROT} and the scaling D_{TRI} of the total probability distribution without change of its Gaussian-like shape. The characteristic parameters of both effects were obtained as a function of TP

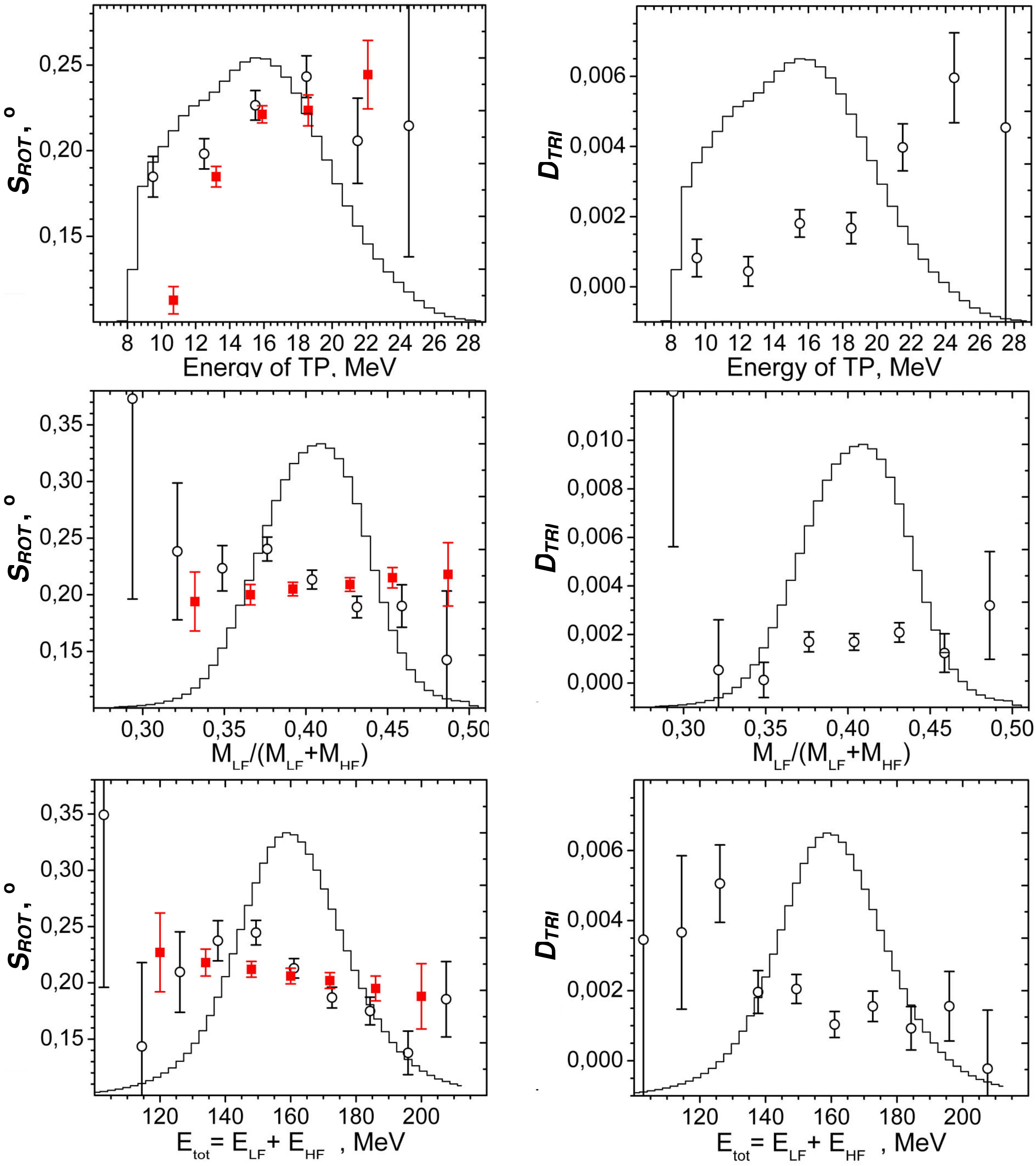

Fig. 4. Dependences of S_{ROT} (left) and D_{TRI} (right) on E_{TP}, M_{LF}, E_{FF} . Open dotes – experimental data, filled squares – result of trajectory simulations for ROT effect. See the text.

energy, FF mass and the total FF kinetic energy. It was demonstrated that despite of the smallness of both effects they are well measurable with spin the flip technique on an intense neuron beam.

Obviously, the ROT and TRI effects depend on many parameters of the fission process – such as the collective characteristics of transition states, the overlap of neutron resonances, the structure of scission configurations, the dynamics, etc. The high sensitivity of the ROT effect was clearly demonstrated in our trajectory calculations [2,4]. Since both effects are closely related to the fission mechanism, their study is thought to be a valuable and sensitive tool for exploring the fission process.

In more detail the general status of ROT and TRI effect studies, their perspectives and possible applications are discussed in a further report at this conference [4].

4. Acknowledgements

This work was performed with the financial support of the foundations RFBR/Moscow (grant 06-02-16668-a) and INTAS/Bruxelles (grant 6417). The authors thank the members of the ILL technical services, who have done the utmost for making these experiments possible.

References

1. P. Jesinger et al., *Nucl. Instr. Methods*, A440 (2000), 618
   P. Jesinger et al., *Yad. Fiz.*, 65 (2002), 662 [*Phys. At. Nucl.,* 65 (2002), 630]
   A. Gagarski et al., *Proc. Int. Seminar ISINN-12*, Dubna, Russia, 2004, 255
2. I. Guseva, Yu. Gusev, *Izvestiya RAN: Ser. Fiz.,* 71 (2007), 382 [*Bull. of the RAS: Physics,* 71 (2007), 367]
   I. Guseva, Yu. Gusev, *Proc. Int. Seminar ISINN-14*, Dubna, 2006, 101
3. F. Goennenwein et al., *Phys. Lett. B*, 652 (2007),13
   A. Gagarski et al., *Proc. Int. Seminar ISINN-14*, Dubna, 2006, 93
4. G. Petrov et al., *Proc. Int. Seminar ISINN-16*, Dubna, 2008, these proceedings
5. Yu. Kopach et al. *Yad. Fiz.*, 62 (1999), 812 [*Phys. At. Nucl.,* 62 (1999), 840]