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A ROOT-based program for analysing data on T-odd asymmetry in the neutron-induced fission of heavy nuclei

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This paper presents a ROOT based program that allows processing the data from experiments on the ROT-asymmetry in the angular distribution of fission products and present the results of the experiment in a convenient and visual form. The program can work with huge data sets and detect very subtle effects. The algorithm used by the program is given in this work. The overall description of the experimental setup, as well as data acquisition and processing systems, are presented, too.

Keywords: data processing program, data acquisition and processing system, ROT-asymmetry, polarized neutrons.

Introduction

An experiment aimed at measuring the ROT-asymmetry in the angular distribution of prompt gamma-rays and neutrons in fission was carried out at the Heinz Meyer-Leibniz research neutron source (FRM II reactor) of the Munich Technical

University in Garching (Germany), on a polarized neutron beam provided by the POLI diffractometer.

It was found that when reversing the direction of polarization of the neutron beam, the angular distribution of prompt γ-rays and neutrons of fission is shifted by a small angle relative to the axis of fragment emission. In this case, the offset direction being determined by the direction of polarization of the neutron beam, causing the fission. This effect was explained in the classical model as a result of the collective rotation of the fissile nucleus at the moment of its rupture [1-2] and named as ROT-effect (from the rotation). Details of these measurements may be found elsewhere [3-6].

The focus of this article is on the description of the data processing program. The processing of the experimental data is a complicated and time-consuming process. The results of any experiment, no matter how carefully they were carried out, are subject to some errors. The analysis of the results and errors of measurement is an essential part of any scientific experiment.

Description of the experiment

The schematic view of the experimental setup at the POLI instrument is depicted in Figure 1.

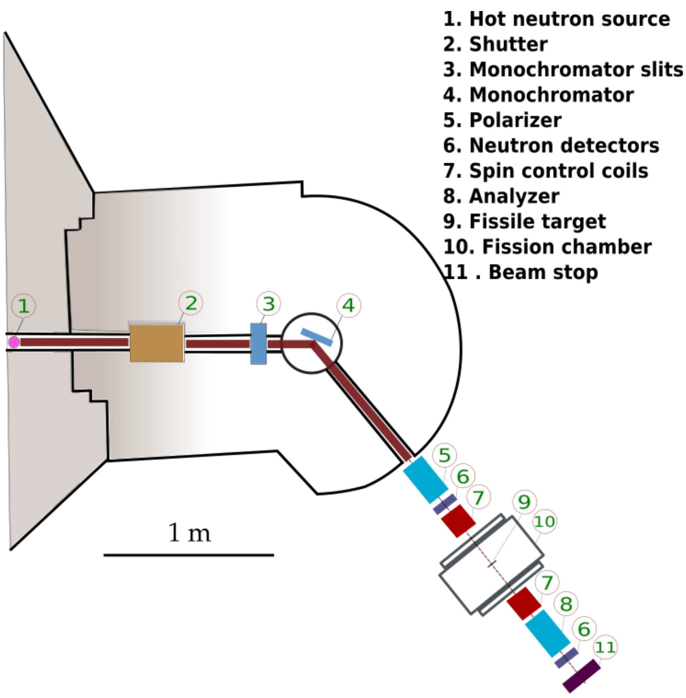

Figure 1. Schematic view of the experimental setup with POLI instrument at MLZ.

The neutrons were polarized using an in-situ SEOP (Spin Exchange Optical Pumping) polarizer [7]. The degree of neutron beam polarization was close to 100 % and was kept constant during the experiment. The monochromatic polarized neutron beam passes through a thin Al window into the cylindrical fission chamber filled with tetrafluoromethane gas (CF_4) at a pressure of about 10 mbar. Si(311) non-polarizing variable double-focusing monochromator was used to produce an intense monochromatic narrow neutron beam.

The two-sided fissile target, containing about 82 mg of ^{235}U oxide-protoxide deposited on the thick 40×100 mm^2 aluminum backing is mounted on the axis of the chamber along the longitudinally polarized neutron beam direction. Two low-pressure multiwire proportional counters (LPMWPC) facing each other to the left and right of the target at a distance 3 cm (start detector) and 11 cm (stop detector) recorded fission fragments. Each stop counter consists of five independent segments at the angles of 0, ± 22.5, ± 45 degrees in the left and ± 135, ± 157.5, 180 degrees in the right side of the target to increase the angular sensitivity of the detector. Prompt fission γ-ray and neutron detectors are located outside the fission chamber. Each of these detectors is a scintillation counter. As a scintillator, plastic and NaI(Tl) crystals were used, which made it possible to effectively register not only γ-rays, but also neutrons. Eight cylindrical plastic scintillators with a diameter of 70 mm and a length of 120 mm and four NaI scintillators optically connected to a photomultiplier tube, wrapped with an antimagnetic screen and placed in a sealed aluminum case were inserted in a rotatable holder at a distance of about 30 cm from the target center. The schematic view of the used detector array inside/outside the fission chamber is shown in Figure 2.

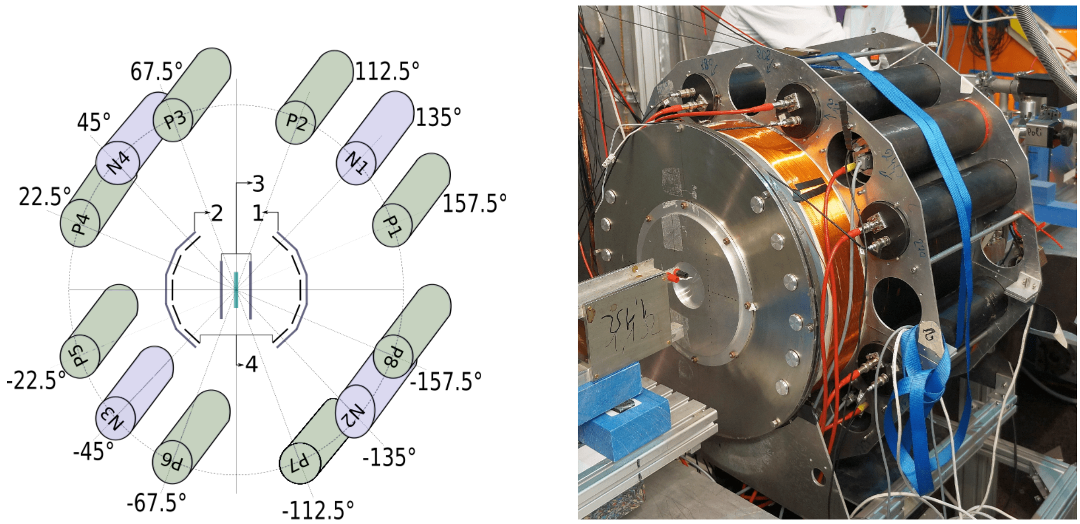

Figure 2. To the left the layout of the detector positioning around the target inside/outside the fission chamber. View from the beam direction. 1, 2 - stop cathode, 3 - start cathode, 4 - stop anode. P1-P8 are plastic scintilators, N1-N4 are NaI scintilators. To the right the photo of the fission chamber surrounded by the scintillator counters.

Plastic detectors, located at the angles of ± 22.5, ± 67.5, ± 112.5 and ± 157.5 degrees ensure subsequent measurements of coincidences of prompt fission γ-rays and fission fragments with respect to the mean axis of the detection of fragments. Prompt neutrons and prompt γ-rays from fission were separated via plastic scintillators using the time-of-flight technique. The start signal was the signal from the fission fragment detectors, which also served as a trigger indicating the fission event. The incoming polarization is periodically flipped between parallel and antiparallel to the beam propagation. Controlled by the quartz clock the spin was flipped by 180° every 1.3 seconds.

Data acquisition system

The data acquisition system (DAQ) of the experiment is used to collect signals from all detectors, to digitize the signals and record them, as well as to adjust and control the operation of the experimental setup. The simplified scheme of the data acquisition system (DAQ) is shown in Figure 3.

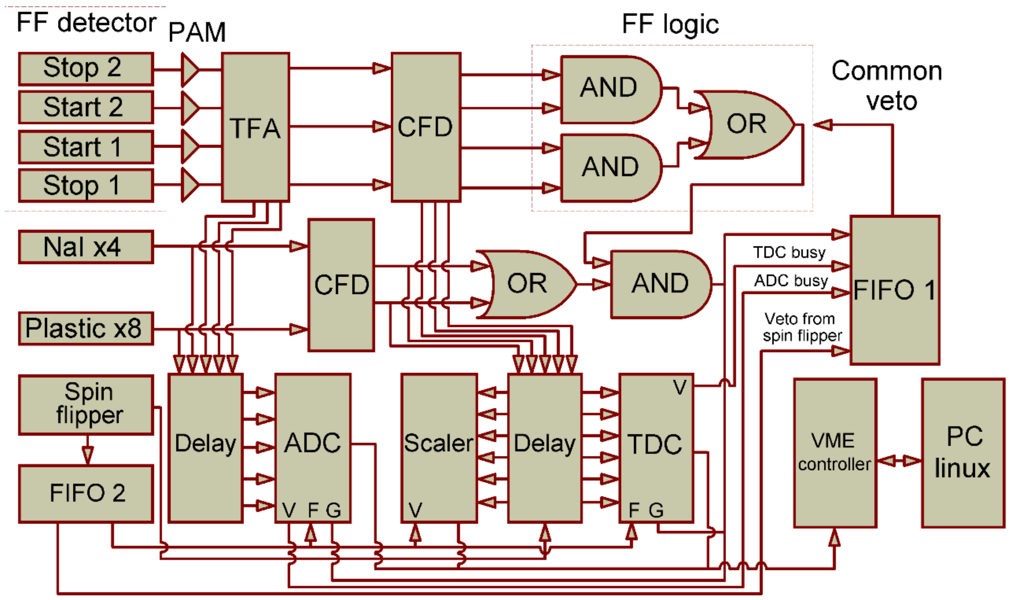

Figure 3. The scheme of the data acquisition system.

To build data acquisition systems, NIM and VME standards were used. They are modular systems consisting of various electronics, made in the form of separate plug-in modules, as well as of standardized digital interface used for computer automation and measurement control. Replaceable modules are placed in one or several crates, which provide the ability to exchange data between different modules on the internal bus. The DAQ of the experiment included the following modules: preamplifiers (PAM), timing filter amplifiers (TFA), constant fraction discriminators (CFD) for time pick-up, Time-to-Digital Converters (TDCs), logical modules AND, OR, Logic fan-in/fanout (FIFO), Analog-to-Digital Converters (ADCs), delays, scalers. A more detailed description of the data acquisition electronics is given in [8].

A general view of the NIM and VME crates with the modules placed in them is shown in Figure 4.

On a computer located in the immediate vicinity of the instrument, a software package was used that controls the operation of the instrument and organizes data acquisition and recording. All data were saved as files in binary format. During one day of measurements, about 5 GB of compressed data was collected, divided into 5-minute expositions. For each exposition two types of data files are created:

- lmd.gz - list-mode data file, containing event-by-event data from all TDC and ADC non-zero channels, for each event the current neutron spin state is also recorded;

- sca.gz - scaler file, containing data from all scalers (counters), recorded during 1.3 seconds interval up to the next spin flip. Both files are gzipped "on the fly".

Figure 4. Data acquisition system of the experiment.

Data processing program

To calculate the effects of T-odd asymmetry for prompt γ-rays and neutrons of fission, a computer program was written in C++ that allows calculating the asymmetry for any possible combinations of angles between fission fragments and prompt γ-rays and neutrons. The algorithm used by the program is presented below:

- The program reads the source data from a text file in which the position of the γ-rays/neutron detectors (angles), the position of the fragment detector, a list of processed files and the path to them are recorded;

- Based on the information read from the text file, the program processes sca.gz files (data from the scaler);

- It is assumed that for each sca.gz file there is the lmd.gz file with the same name. In the lmd.gz file, time-of-flight spectra are recorded, that is, the results of digitization of all TDC channels, as well as information about the spin of the incident neutron. The program processes only the corresponding lmd.gz files.

- The processing results are recorded in a text file, and also histograms are built on their basis, for which the ROOT library is used.

- The obtained experimental results are approximated by the formula, and thus the ROT-asymmetry and the rotation angle of the fissile nucleus before its rupture are determined.

Analysis of sca.gz files

In order to correctly read data from files stored in binary form, the general storage structure inside the file is recorded in the corresponding header file (the number of bytes occupied by the type and the sequence of bytes). The data recorded in a sca.gz file represented by the structure consisting of 40 elements. The first 16 elements contain data from the counters (shaped output signals from the fission fragment and γ -ray detectors, from the neutron detectors placed after polarizer and after analyzer, as well as signals from the quartz generator, were fed to the counter′s input). The remaining elements recorded important information, such as spin, number of events, "good" events, not valid data, bad tdc-adc counters, event buffer overflow, spin-flip error, lmd.gz file write error, sca.gz file write error, VME error.

Based on the read data, the program builds graphs and saves them as root-files. Each parameter is represented as a graph showing the dependence of the parameter on the number of spin flips passed since the beginning of the experiment.

The data from counters were used to control the status of the setup and instrument asymmetry. The program excluded from exposure processing in which was observed a significant (more than 5 standard deviations from zero) asymmetry in at least one of the counters. Such a deviation may occur in the case of an abrupt change in the reactor power and, as a consequence, the neutron beam intensity.

Since the incident neutron beam spin-flip served as one of the main mechanisms for suppressing instrument asymmetry, special attention was paid to the stability of the measurement time for opposite values of the neutron spin (spin takes two values, "1" when the neutron spin is directed forward and "0" - backward along the beam propagation direction). Figure 5 shows an example of a spin-flip, read from a sca.gz file. Files with spin-flip errors (e.g., wrong order of spin flips) are programmatically ignored.

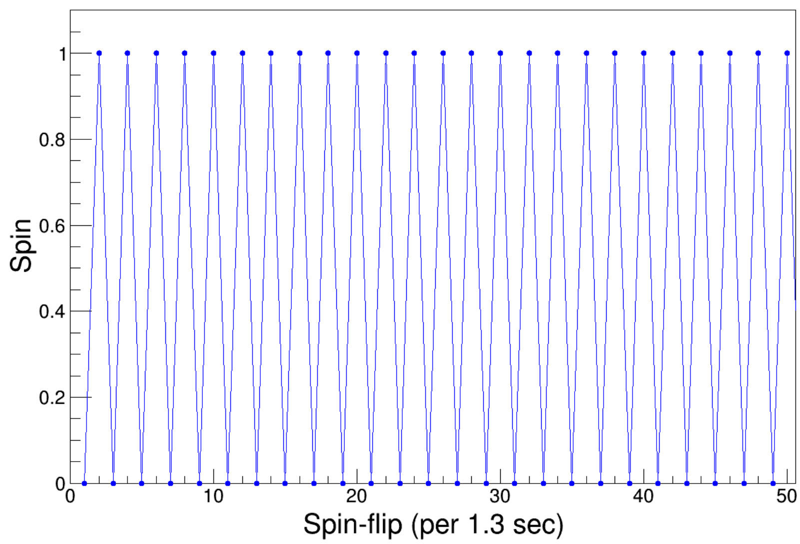

Figure 5. Example of a sequence of spin flips of a polarized neutron beam.

Analysis of lmd.gz files

The program searches for a lmd.gz file with the name corresponding to the sca.gz file. When it does not find any file it passes the next step and reads the compressed lmd.gz file. Based on these data, histograms are filled and saved as a root-file.

To reduce the systematic effect, the expositions were excluded from processing during which the data acqusition rate changed significantly (the size of the exposition data file differed from the data file size of one of the neighboring exposition by at least 5 %).

The program compares spins read from the sca.gz file and from the lmd.gz file. In case of mismatch, it shows an error and ignores these data in the processing.

As mentioned above, the time-of-flight technique was used to record the events of fission and separate prompt γ-rays from neutrons. The program sets time intervals in the time-of-flight spectra that discriminate neutrons from γ-rays (Figure 6, left) and separate the segments of the stop detector (Figure 6, right). Each stop fragment detector consisted of 5 segments connected in a chain seperated by delay lines and fed into one TDC channel. The time of arrival of the signal relative to the start detector indicated which segment was hit by the fission fragment. The number of events is determined by integration (inside the color-shaded area).

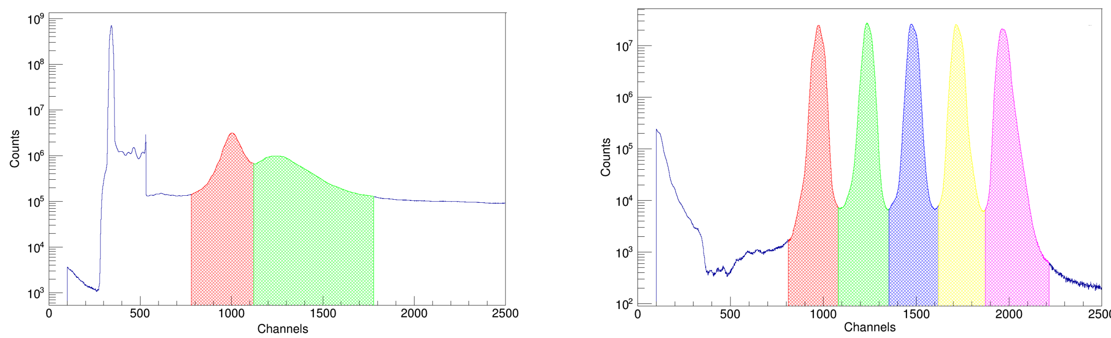

Figure 6. Time-of-flight spectruma of one of the plastic scintillators (left) and one of the stop detectors (right).

The program writes to the array the results of the coincidence of pulses from eight independent plastic detectors with each pulse from ten segments of the stop detector. Due to the symmetry of the experimental setup it makes 16 different relative angles between the axes of the fission fragment and γ-ray detectors in the experiment. Then program determines the T-odd asymmetry coefficients of the number of coincidences of prompt fission γ-rays and fission fragments with respect to the direction of neutron beam polarization for each angle, calculated by the formula:

$$R(\theta) = \frac{N^{+}(\theta) - N^{-}(\theta)}{N^{+}(\theta) + N^{-}(\theta)}, \quad (1)$$

where $N^{+}(\theta)$ and $N^{-}(\theta)$ are the γ-ray count rates for a selected angle between the detectors at two opposite directions of neutron polarization. It also determines errors by the formula:

$$\sigma = \sqrt{\frac{R(\theta) - 1}{N^{+}(\theta) + N^{-}(\theta)}}. \quad (2)$$

These calculation results are written to a text file, separately for the plastic detector and NaI scintillator. Figure 7 shows the result of processing of the experimental data on the ROT-effect in binary fission of ^{235}U by monochromatic polarized neutrons with an energy of 62 meV.

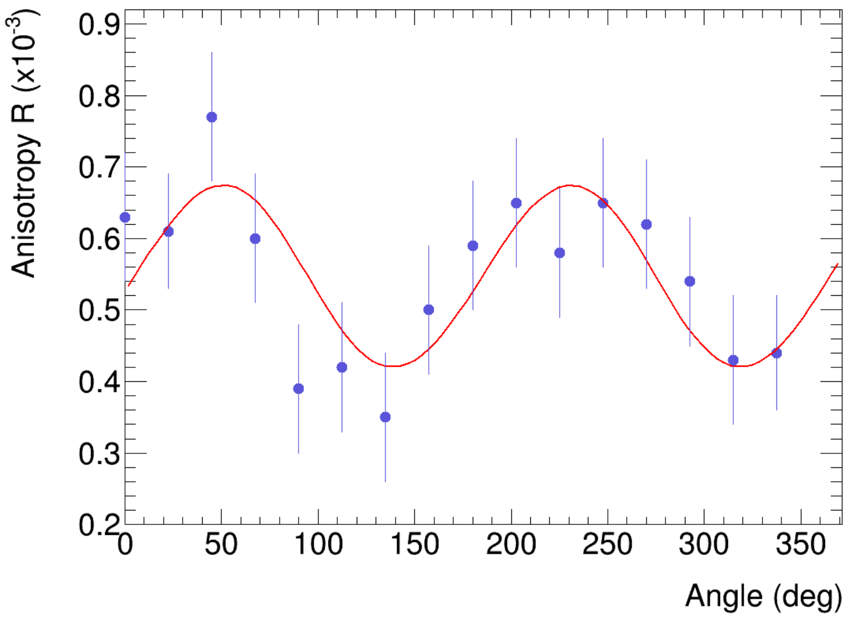

Figure 7. Anisotropy ratio R as a function of angle between the γ -ray and fission fragment detectros.

Conclusion

A program has been written to calculate the ROT-asymmetry in the angular distribution of prompt γ -rays and neutrons of fission. The program sorts coincidence data according to the neutron spin orientations. It allows calculating the asymmetry for any possible combinations of angles between fission fragments and prompt γ -rays and neutrons. It also calculates errors according to the processed data.

The processing results are saved in a text file and in the root-file containing histograms and graphs.

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