Ternary particles of Z =1 to 6 emitted in spontaneous fission of ^{252}Cf

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Outline

- Motivation
  - Rare fission mode processes: ternary, quaternary, and quinary
  - Detection of rare events: position, direction, energy, time/coincidence, decay
- Instrumentation & Tools
  - Timepix detector
  - USB-based R/O interf. (power, control, DAQ)
  - Synchronization system
- Methods & Experiments & Results
  - Principle of the experiment and experimental setup
  - dE-E particle identification
  - Data analysis
  - Ternary fission results
- Conclusion and future plans

Motivation, Tasks, (long term) Goals

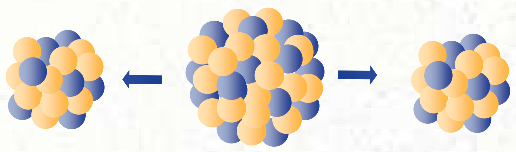
- Limitations arise from the standard solid state detectors used so far and can be solved simultaneously by highly segmented single-quantum counting pixel detectors.
- Timepix which is equipped with energy and time sensitivity capability per pixel, provides high granularity, wide dynamic range and per pixel threshold.
- Can provide multi-parameter event-by-event spectroscopic information (position, energy and time, particle type) of basically all types of charged particles
- Furthermore, combination with event track analysis provides enhanced signal to noise ratio with a high suppression of background and unwanted events.
- Timepix can combined with a ΔE detector and further operate also as a ΔE detector

Rare fission mode processes: Position sensitive spectroscopy of fission fragments

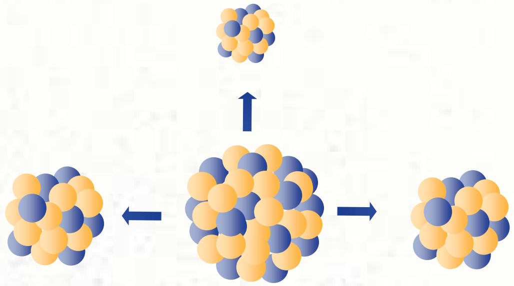
- Measurement of angular and energy distributions of ternary and quaternary particles.
- Determination of quaternary fission yields with high accuracy and sensitivity.
- Direct observation of ^{8}Be emission as a ternary particle in the ground and excited state.
- Search for other rare decay modes in fission – e.g. quinary fission ($^{12}C^{*} \rightarrow \alpha+\alpha+\alpha$), Collinear fission?
- Measurement of H^1, H^2 and H^3 ternary particles and estimation of their yields.

Ternary Fission / Introduction

Binary Fission



Ternary Fission



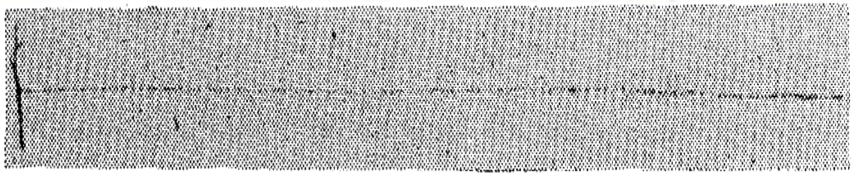
The two heavy fragments are sometimes accompanied by a Light Charged Particle (LCP): Ternary fission

The possibility of fission into three charged nuclei has been pointed out by theoretical physicists, predicting a liberation of maximum energy of 210-220 MeV, even 10-20 MeV higher than that of binary fission.

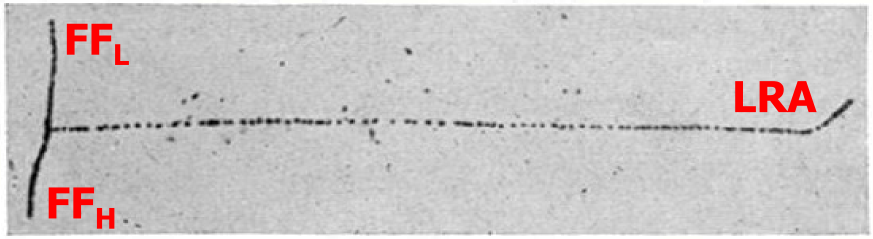
- N.Bohr and J.A.Wheeler, Phys.Rev.50, 426 (1939)
- R.D.,Present, Phys.Rev.59, 466 (1941)

Experimentally observed for the first time in 1946

Ternary fission: third fragment—mass-6, range=44 cm air equivalent.



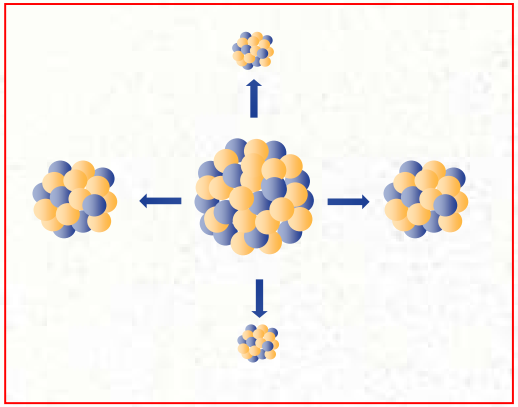
Ternary fission: third fragment—mass-9, range=17 cm air equivalent.



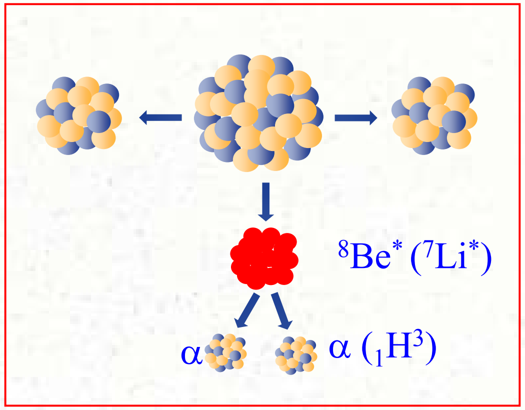
- Tsien San-Tsiang, Phys. Rev. 71 (1947), 382
- L. W. Alvarez, as reported by G. Farewell, E. Segre and C. Wiegand, Phys.Rev.71, 327 (1947)

Quaternary Fission / Introduction

“True” Quaternary Fission



“Pseudo” Quaternary Fission

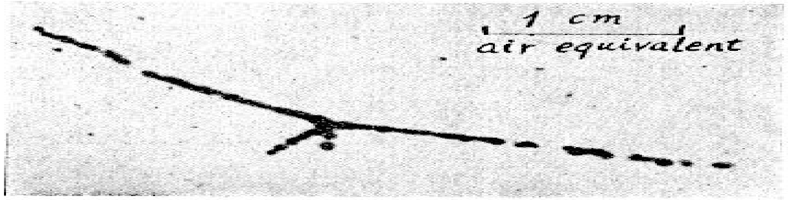


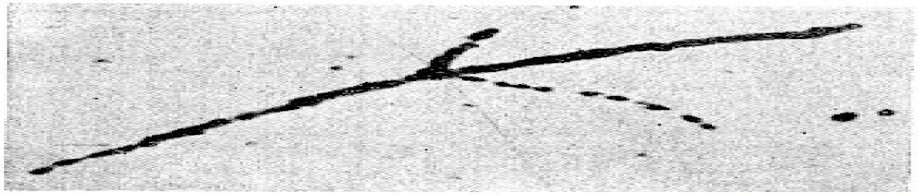
The two heavy fragments are sometimes accompanied by two Light Charged Particle (LCP)

- N.Bohr and J.A.Wheeler, Phys.Rev.50, 426 (1939)
- R.D.,Present, Phys.Rev.59, 466 (1941)

Experimentally observed for the first time in 1946

Tsien San-Tsiang, Phys. Rev. 71 (1947), 382

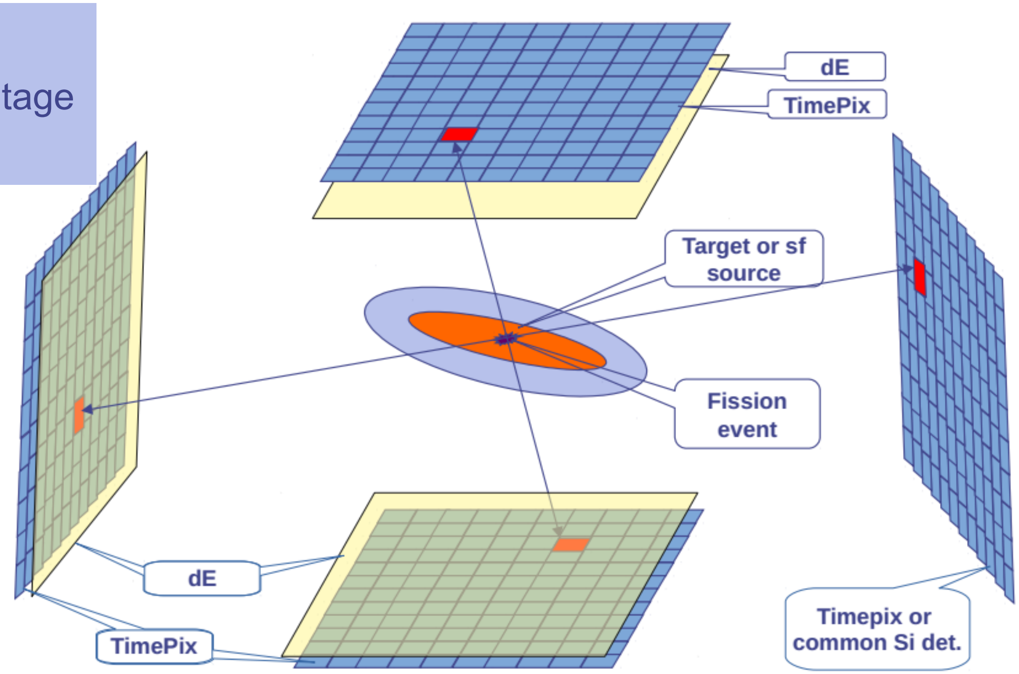




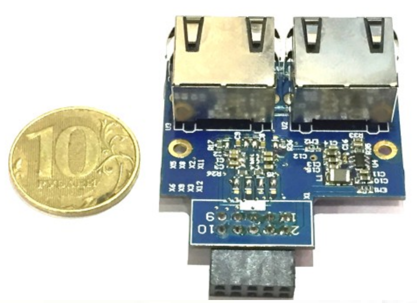
Principle of the experiment and experimental setup

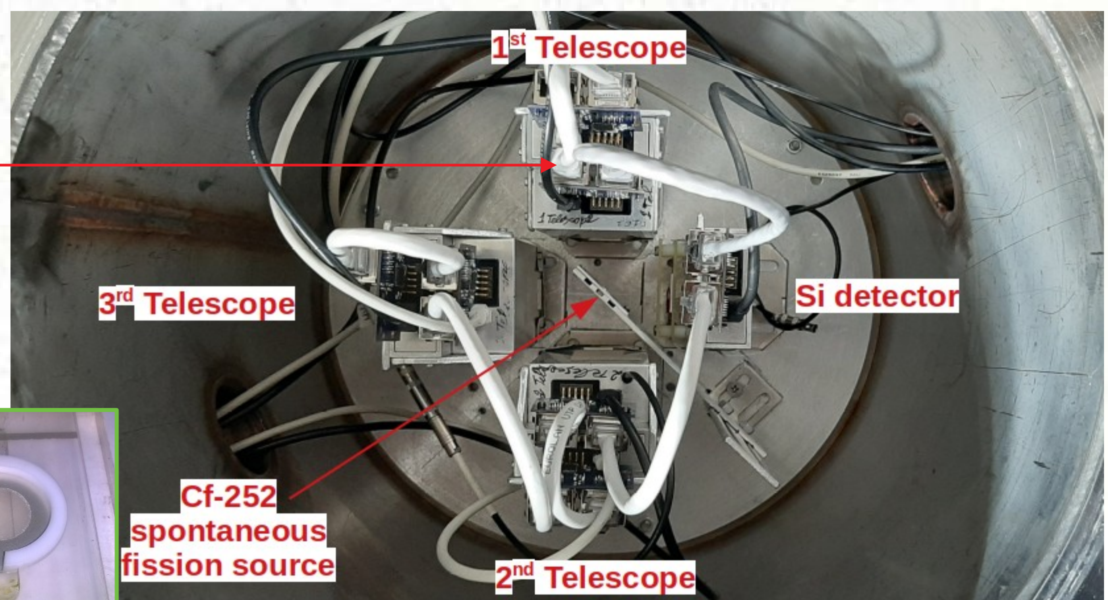
- Four detectors in coincidence
- PAM+Amp+ADC+trigger+bias voltage
- USB based experimental setup

target : ^{252}Cf, ^{235}U, ^{239}Pu etc.



Synchronisation module

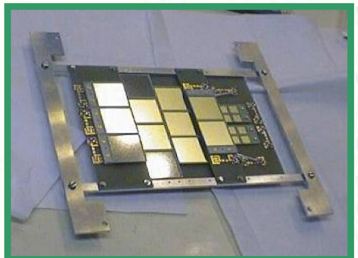


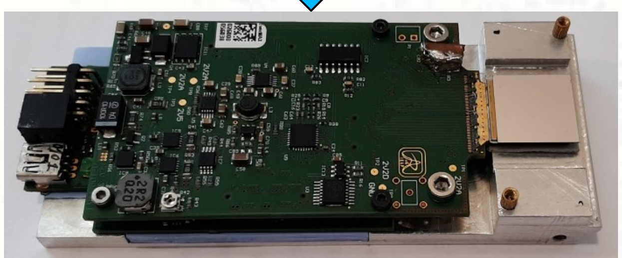


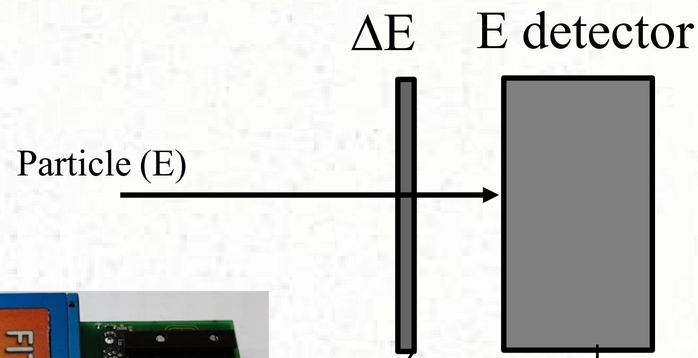
ΔE-E telescopes based on Timepix detector

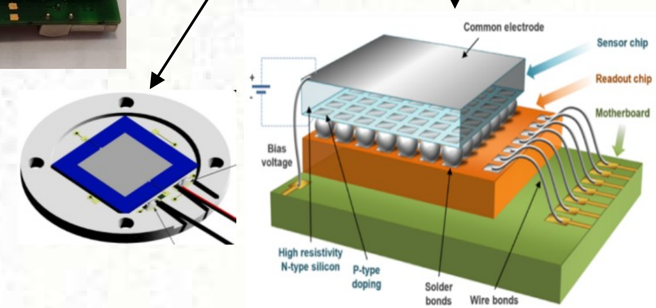
The incoming particle passes the thin detector, loses energy, and gets absorbed by the thicker detector. The signal from the thin detector is proportional to dE/dx, where E is the energy of the particle. The thicker detector measures the remaining energy. An identification of particles can then be made by comparing their energy losses in the thin detector to the energy deposited in the thick one. This is possible because different particles have different stopping powers in the silicon, according to the Bethe-Bloch formula. Timepix is a detector consisting of 256*256 number of 55*55 um pixels.

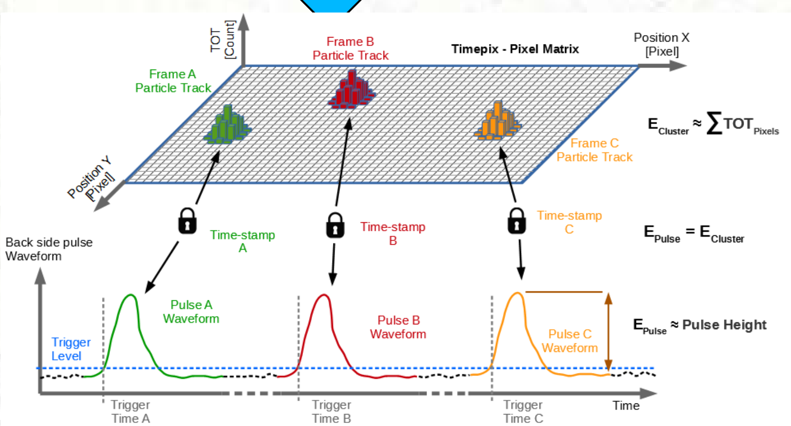
$$\Delta E \Leftrightarrow -dE/dx \approx (aZ^2)\cdot \ln [b\beta^2\gamma^2]$$







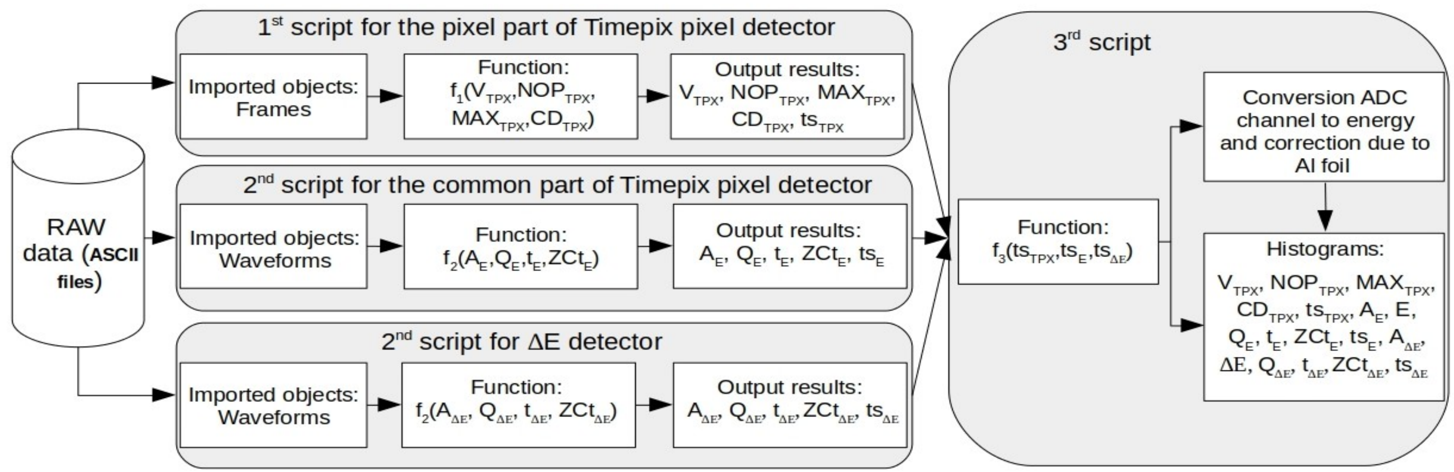


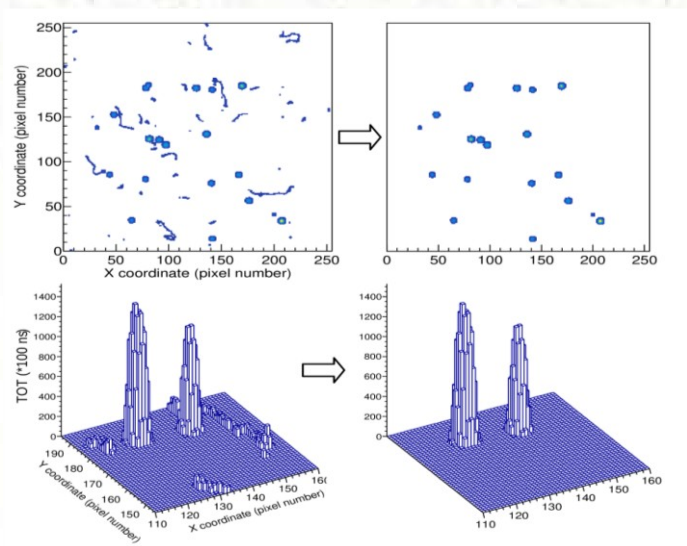


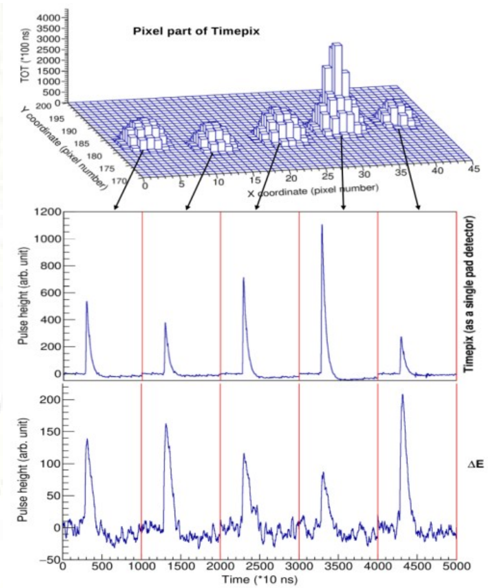
E- Timepix (300 μm, 600 μm)
Timepix → E, θ, t
ΔE- Thin PiN detector (15 μm, 150 μm)
ΔE→ z (particle type)

Data analysis

A ROOT based program, consisting of many scripts for analyzing and/or filtering ternary and quaternary fission particles among various fission events. The program can process long collected files in ASCII and binary formats, compare the results from all detectors, give results in terms of particle interaction time, coordinates, particle energy and their types.

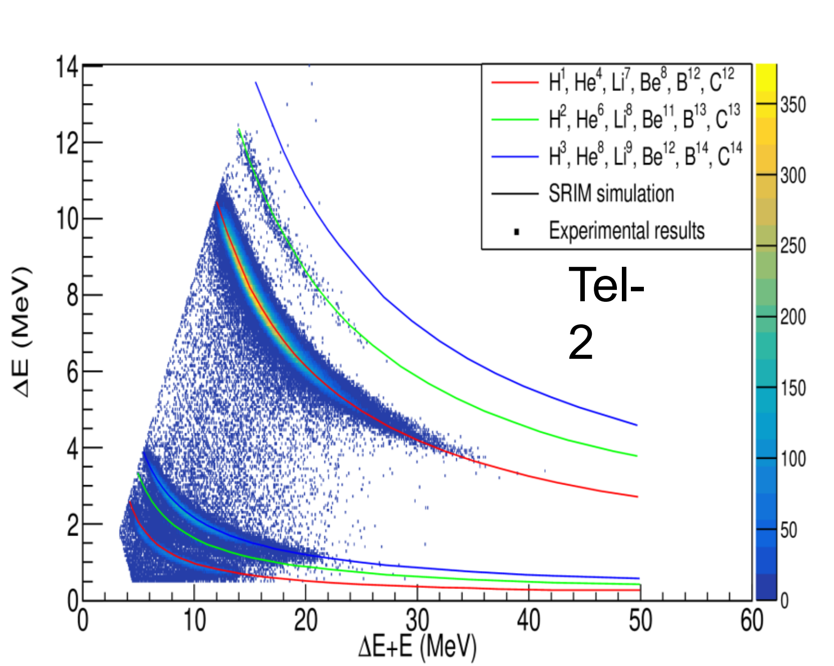


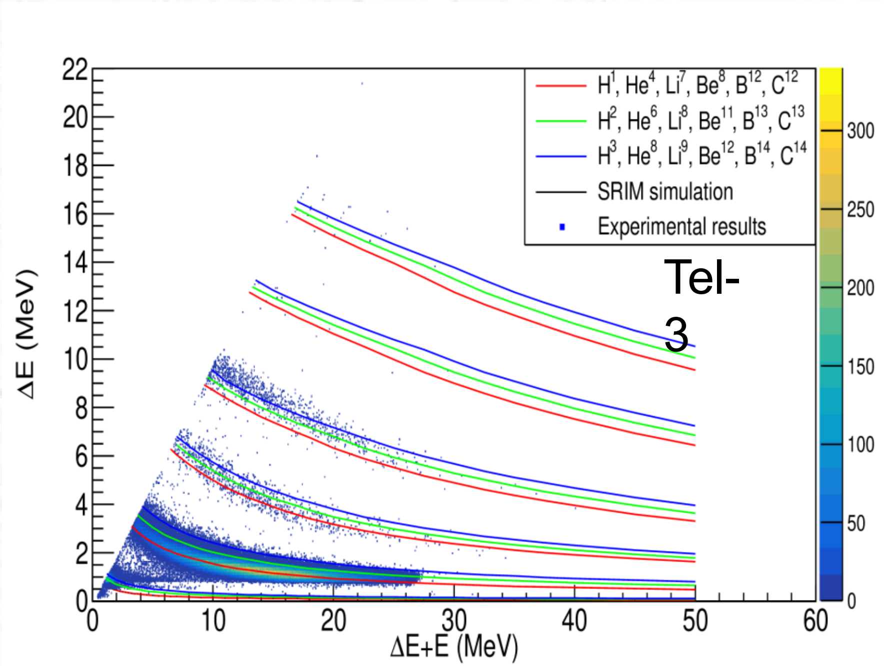




2D spectra from ΔE-E telescopes

The experimental ΔE-E scatter plots were analyzed and compared with the results from the nuclear simulation program SRIM. The lines represent SRIM calculations for energy loss of each particle. A good agreement between the experimental and simulated data as well as a good detector performance were found. Spectra were presented without corrections in Al foil (30 um). ΔE detector thicknesses were 150 and 15 um, respectively.



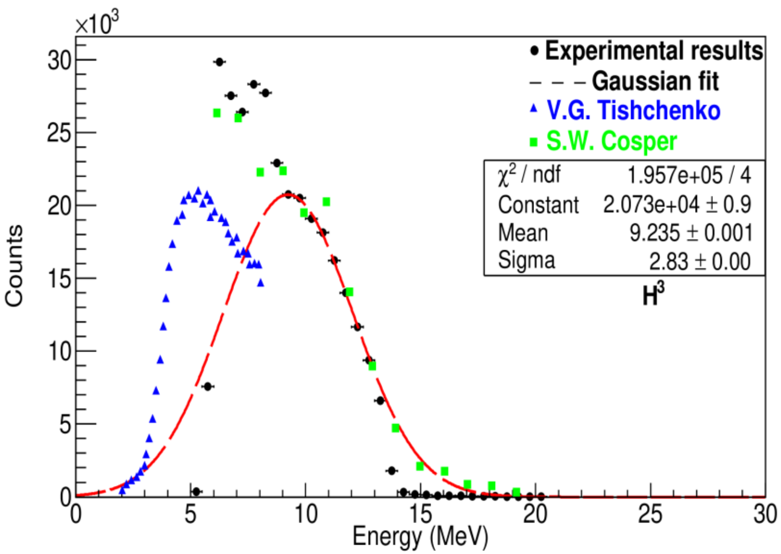


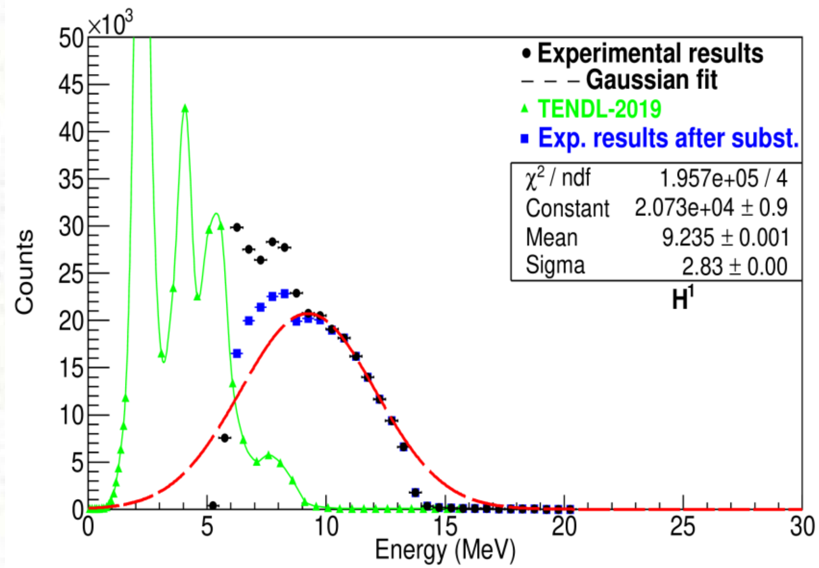
^{252}Cf – ternary fission: H^1

The proton energy distribution obtained from this investigation is presented. The spectrum appears to be composed of three separate energy distributions. In order to determine whether the protons of components were associated with the intense 6.2 MeV alpha particles from the ^{252}Cf source, Talys-2019 calculations were done.

Since the average energy of neutrons released from ^{252}Cf is 2 MeV, the energy of protons produced by Al (n,p) reaction at these energies is up to 2 MeV. The experimental setup does not allow registering such protons. In general, the energy of neutrons released from ^{252}Cf can be up to 10 MeV. However, the probability of emission of neutrons decreases sharply depending on energy of neutrons. Therefore, the protons released during the (n,p) reaction with high-energy neutrons can be ignored.

Energy spectrum for H^1 was corrected for loss in the aluminum absorber foil (30 um).

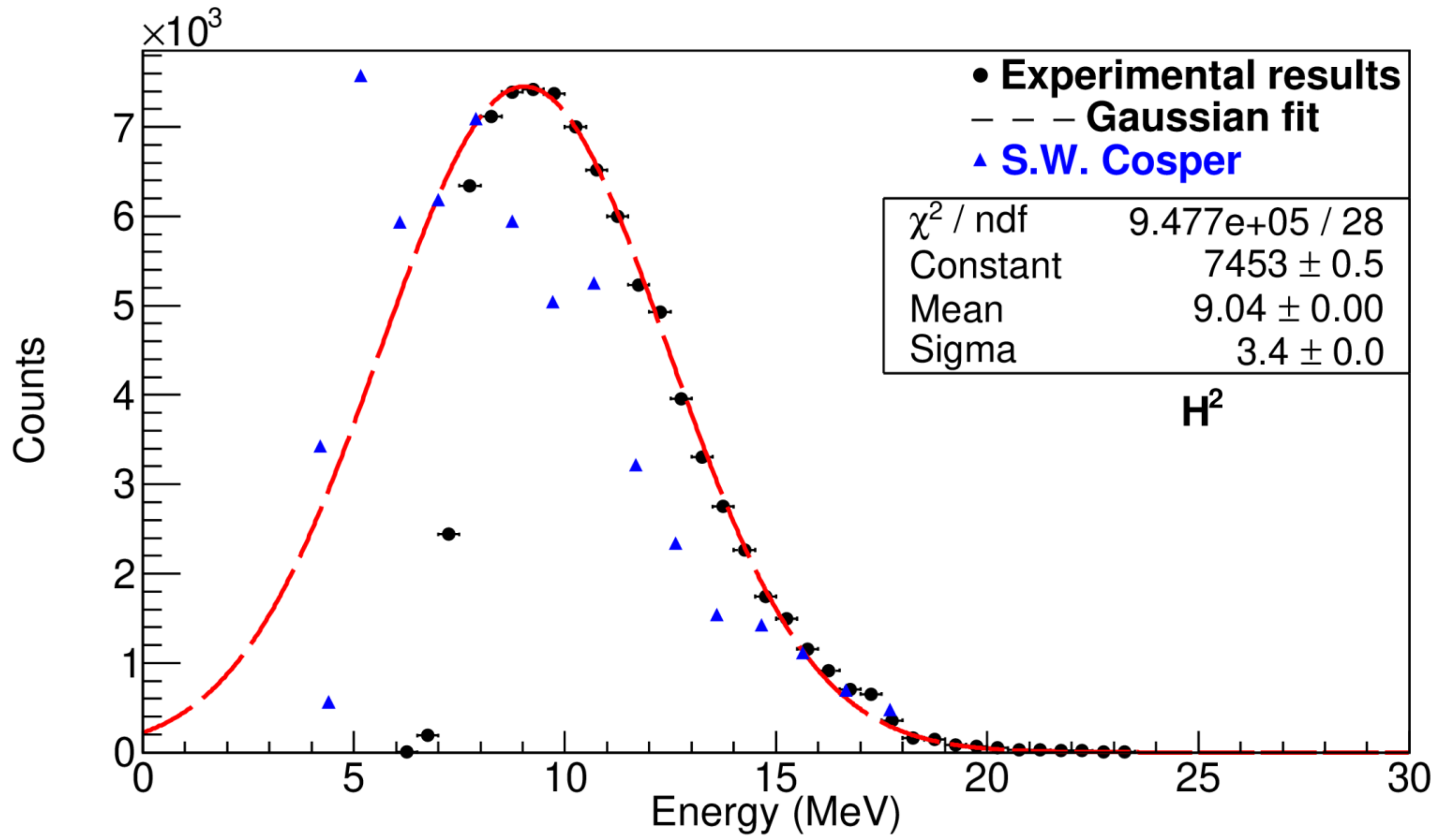




1. Tishchenko V. G. et al. Study of Ternary and Quaternary Spontaneous Fission of ^{252}Cf with the NESSI Detector. Report HMI-B 588. 2002.
2. S.W. Cosper, J. Cerny, R.C. Gatti, Phys. Rev. 154, 1193 (1967).

^{252}Cf – ternary fission: H^2

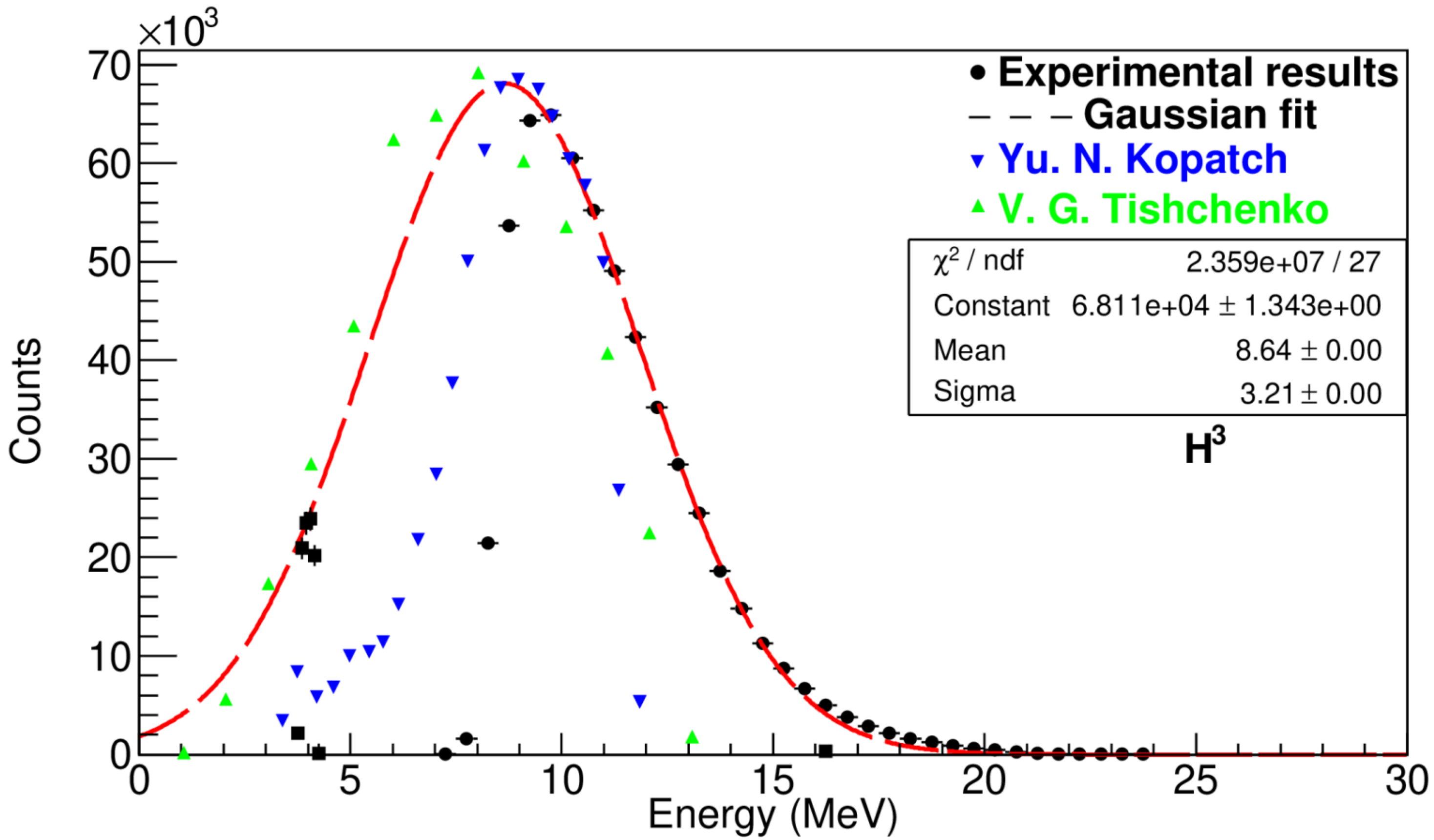
Energy spectrum for H^2 was corrected for loss in the aluminum absorber foil (30 um).



S.W. Cosper, J. Cerny, R.C. Gatti, Phys. Rev. 154, 1193 (1967).

^{252}Cf – ternary fission: H^3

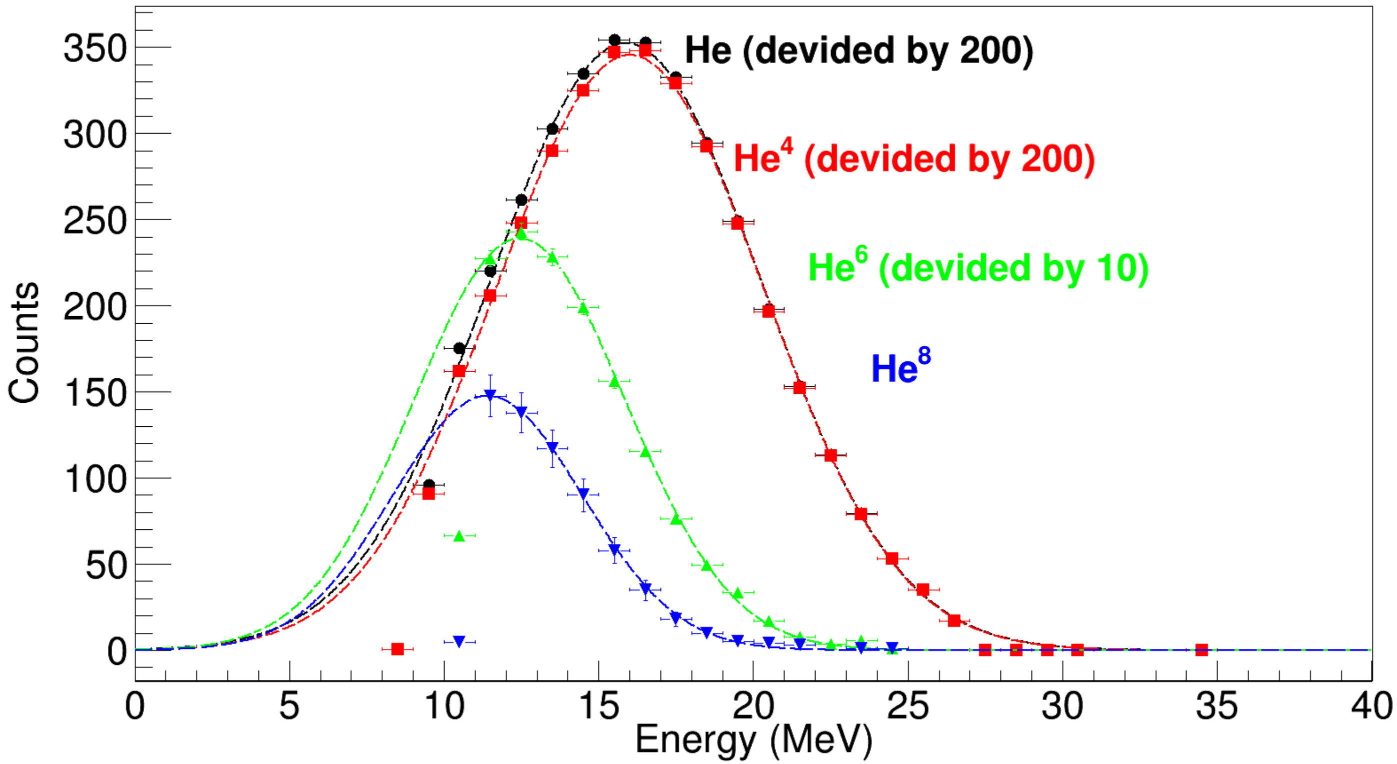
Energy spectrum for H^3 was corrected for loss in the aluminum absorber foil (30 um).



[1]Yu. N. Kopatch, M. Mutterer, D. Schwalm, P. Thirolf and F. Gonnenwein, Phys. Rev. C 65 044614 (2002).
[2]Tishchenko V. G. et al. Study of Ternary and Quaternary Spontaneous Fission of ^{252}Cf with the NESSI Detector. Report HMI-B 588. 2002.

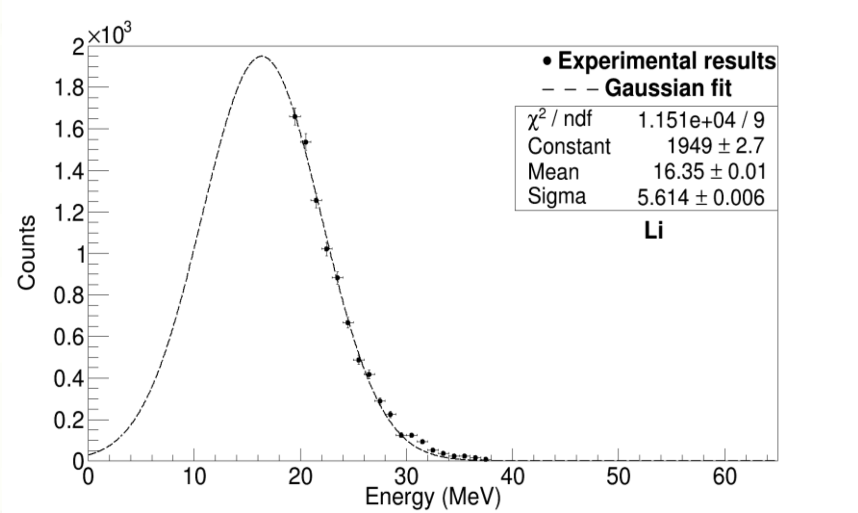
^{252}Cf – ternary fission: He isotopes

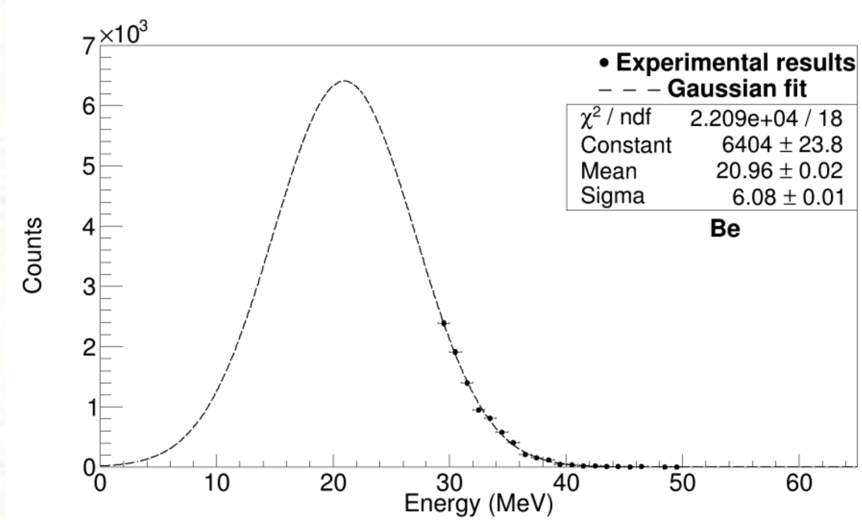
He isotopes was analyzed and the contribution of isotopes to whole He spectrum was shown.

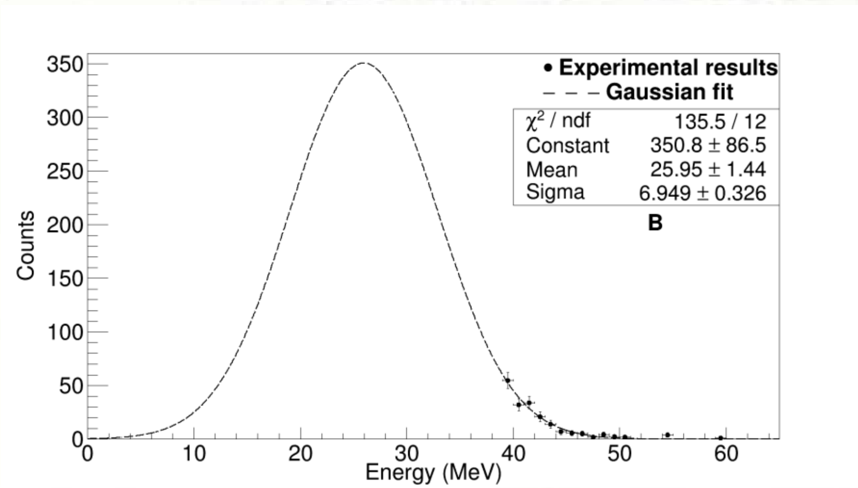


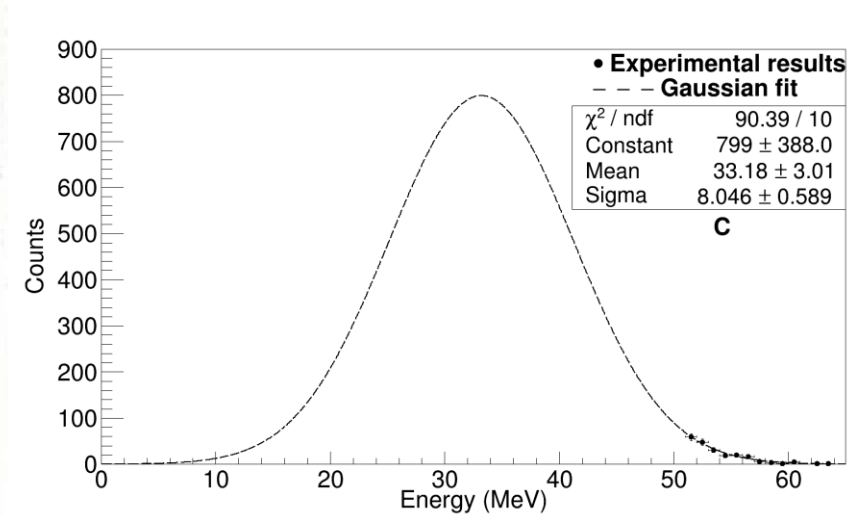
^{252}Cf – ternary fission: other particles

Al foil was placed in front of the detectors in order to protect the telescopes from the intense flux of FFs and alphas (6.2 MeV). Thickness of ΔE detector leads to cut-off energies, too. As to be observed in Figures, the heavier the LCPs are, the higher is the fraction of particles which are lost for detection. From experimental data where the full energy spectra could be measured, it is established that the LCP distributions are well represented by Gaussian. Therefore all energy distributions were assumed to be satisfactorily described by Gaussian fit.









Results

The information obtained on the total yields of each of the particle types is presented in Table. All yields are normalized to 10^4 α-particles from the respective reaction.

Ternary particles	Energy (MeV)	Sigma (MeV)	Yield per 10^4 α	Energy (MeV) (Ref.)	Yield per 10^4 α (Ref.)
H^1	9.23(0.16)	3.30(0.13)	133(8)	9±2[1]	160(20)[1]
H^2	9.04(0.14)	3.63(0.07)	57(3)	7±2[1]	63(3)[1]
H^3	8.62(0.58)	3.08(0.03)	495(7)	7.8±0.1 (Tishchenko V. G. et al.)	590(20)[1]
He^4	15.91(0.03)	4.11(0.03)	10^4 (72)	15.7± 0.2 (Wagemans et al.) 15.7± 0.2 (Kopatch et al.) 15.7± 0.1 (Tishchenko et al.) 15.8± 0.1 (Grachev et al.)	10^4(350)
He^6	12.44(0.01)	3.42(0.01)	274(20)	12.6±0.5[4]	310(20)[4] 410(50)[5]
He^8	11.23(0.04)	3.21(0.04)	16(4)	10.2±1.0[6]	25(5)[6]
Li	17.33(0.65)	5.14(0.21)	51(6)	14.3±1.0 (Kopatch et al.)	52(5)[2]
Be	22.11(1.73)	6.13(0.2)	154(36)	18.0(4) (G. M. Ter-Akopian et al.) 17.5(1.0) (M. Mutterer et al.)	126(30)[2] 166(30)[3]

[1]S. L. Whetstone and T. D. Thomas, Phys. Rev. 154, 1174 (1967).
[2]P. Singer, Ph.D. Thesis (TH Darmstadt, 1997).
[3]Yu N. Kopatch, V. Tishchenko, M. Speransky et al., AIP Conference Proceedings 798, 115–122 (2005)
[4]Yu. N. Kopatch, M. Mutterer, D. Schwalm, P. Thirolf and F. Go¨nnenwein, Phys. Rev. C 65 044614 (2002).
[5]M. Mutterer, Yu. N. Kopatch, S. R. Yamaledtinov et al., PHYSICAL REVIEW C 78, 064616 (2008)
[6]https://web-docs.gsi.de/~wolle/FISSION/ternary/node2.html

Conclusions & Future plans

- ✓ A special system (Spectrig) was developed to read and control silicon or semiconductor detectors
- ✓ A special synchronization system was developed and integrated into the electronics. Veto “arbitrer” module: full synchronization
- ✓ An experimental setup based on these systems has been created to study rare fission modes. Coupling/trigger to dE/dx detector
- ✓ A new method of pixel calibration has been proposed for Timepix pixel detectors using Spectrig devices and timing buses
- ✓ Experiments were carried out with a high activity (500 kBq) spontaneous fission source ^{252}Cf: dE/dx particle identification method was successfully implemented for isotopes from H to C
- ✓ Algorithms for data analysis was proposed
- ✓ Energies and yields of ternary particles were determined
- ✓ Data were collected for quaternary fission

❑Rare fission modes

- Analysis of data for quaternary fission is in progress
- Replace Timepix to Timepix 3
- Replace FF Si detector to a multiwire proportional counter
- Increasing efficiency of the detection system
- Search for other rare decay modes in fission – e.g. quinary fission ($^{12}C^* \rightarrow \alpha+\alpha+\alpha$), Collinear fission?
- Neutron induced rare fission modes (^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu et. c.)

Thank You very much for Your attention!