THE EXPERIMENTAL ARRANGEMENT AND PRELIMINARY RESULTS OF SEARCH FOR LIGHT NEUTRON CLUSTERS IN ^{235}U NUCLEI DECAY

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Investigation goal

- Problem of neutron clusters existence is still of scientific interest – recent publications [1,2]
- The results are of special interest for astrophysics and nuclear physics;
- The experimental investigations may encourage new theoretical studies of neutron clusters existence;
- In addition to this, they may encourage the discussion on the previous experimental results.

1. F. Miguel Marqués Eur. Phys. J. Plus **136**, 594 (2021)
2. F. Miguel Marqués, J. Carbonell Eur. Phys. J. A **57**, 105 (2021)

History of neutron clusters search

- Many methods were used to search neutron clusters since early 1960s;
- Pion probe: double charge exchange reaction with pions, e.g. $^{4}He(\pi^{-}, \pi^{+})^{4}n$;
- Only upper limits were set; this technique is practically unused at this moment;
- Activation probes: heavy nuclei emit the clusters -> they interact with the target material nuclei and activate them -> unstable activated target nuclei decay -> decay products are registered
- Detraz et al. (1977) - $^{6,8}n$ systems are claimed to be found in experiments with natural Zn targets;
- Novatsky et al. (2012) – ^{A}n systems $(A \geq 6)$ in experiments with ^{88}Sr and ^{27}Al
- Multinucleon-transfer probe: nucleons exchange in nuclei collisions;
- Cerny et al. (1974) - ^{4}n in $^{7}Li(^{7}Li, ^{10}C)^{4}n$ and ^{3}n in $^{7}Li(^{7}Li, ^{11}C)^{3}n$ reactions;
- Direct registration of neutrons from cluster: probability of registration of 1-3 neutrons from cluster is higher than of 1-2 spontaneous fission neutrons;
- Bystritsky et al. (2016) - $^{6,8}n$ systems are claimed to be found in ^{238}U decay;

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History of neutron clusters search

- GANIL experiment (2002):
- Pre-formation of ^4n in neutron-rich nuclei similar to the formation of α particles in nuclei;
- $^{14}Be \rightarrow {}^{10}Be + {}^4n$ reaction;
- Coincidence system in detection technique: momentum transfer to the detector nuclei (protons of scintillator) from ^4n + direct ^{10}Be registration;
- 6 events with higher proton recoils than from individual neutrons were registered;
- These are claimed to be tetraneutrons, with the coincidence of ^{10}Be registration;
- RIKEN experiment (2016):
- Missing mass spectrum of $^4He(^8He, {}^8Be)^4n$; $^8Be \rightarrow 2^{\alpha}$ was accumulated;
- High Q-value of $^4He(^8He, {}^8Be)^4n$ reaction should allow the formation of ^4n with small momentum transfer;
- Existence of tetraneutrons ^4n was claimed with the confidence level CL = 4.9σ;

1. F. Miguel Marqués Eur. Phys. J. Plus **136**, 594 (2021)

Detection technique

- Cluster decay of heavy nuclei was discovered in 1968;
- Average energy of cluster is 1-1.2 MeV per nucleon;
- Cluster probability decay is lower than probability of α emission or spontaneous fission: $\frac{\lambda(6n)}{\lambda_\alpha} \leq 9.3 \cdot 10^{-9}$; $\frac{\lambda(6n)}{\lambda_{sf}} \leq 1.68 \cdot 10^{-2}$ for ^{238}U [3];
- Probability to register 1-3 neutrons from cluster is higher than to register 1-2 spontaneous fission neutrons (of avg. ≈ 3 fission neutrons) [3];
- Our method is based on idea that neutron cluster is stable in nucleus, but as it leaves nucleus with some momentum, it becomes unstable;
- Cluster decays into the "jet" of neutrons directed to the primary momentum direction of cluster before decay;
- This "jet" of neutrons may be registered as the sequence of signals from neutrons within specified time range;

3. V.M. Bystritsky et al., Int. J. Modern Phys. E **26,** 3 (2017)

Detector efficiency

- It is a must to know the efficiency of neutrons detection in chosen conditions.
- It can be found from the ratios between number of events, where different neutron multiplicities were registered.

- The probability to register *m* neutrons from spontaneous fission with *k* emitted neutrons is described as noted in [4]:

$$M_m = \sum_{i=m}^{k} \mathrm{C}_{\mathrm{m}}^{\mathrm{i}} P_i \varepsilon^m (1-\varepsilon)^{i-m}, \qquad (1)$$

here $\mathrm{C}_{\mathrm{m}}^{\mathrm{i}}$ is number combinations *(m, i);* ε – neutron detector efficiency, *P(i)* is the probability that *i* neutrons are emitted.

- *P(i)* are well known for spontaneous fission events for different isotopes of heavy nuclei;
- Probability to register *x* neutrons from cluster with multiplicity *k* [3]:

$$M_x = C_x^k \varepsilon^x (1-\varepsilon)^{k-x}, \qquad (2)$$

here ε – neutron detector efficiency determined with fission source by (1); $\mathrm{C}_{\mathrm{x}}^{\mathrm{k}}$ is number of combinations *(k, x)*

3. V.M. Bystritsky et al., Int. J. Modern Phys. E **26,** 3 (2017)
4. H. Nifnecker Nucl. Instrum. Methods **81**, 45 (1970)

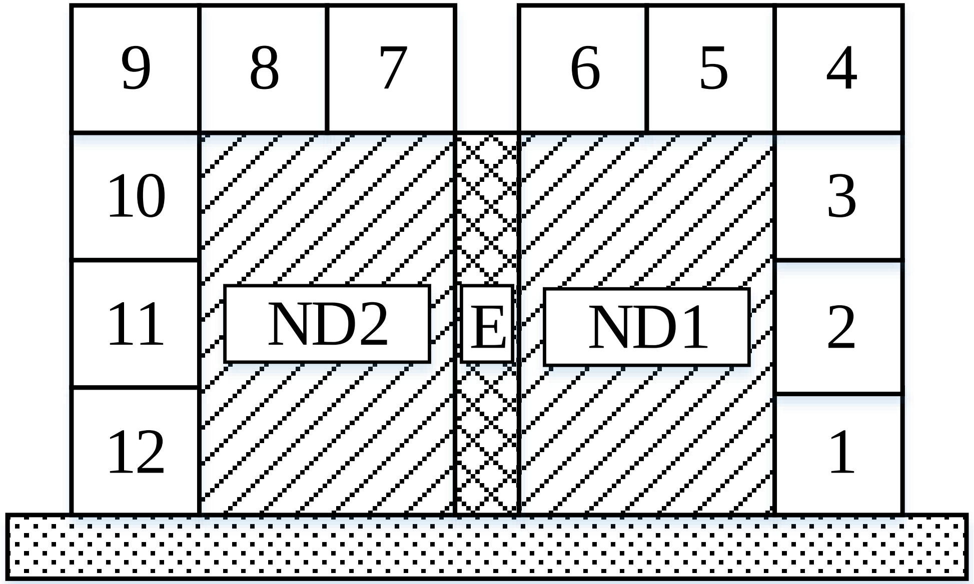
Experimental unit: technical details

- Main detectors part must contain 2 ^{3}He detectors;
- Neutron clusters emitter – enriched UO_3 (90% ^{235}U, 10% ^{238}U) powder placed between detectors;
- The unit must exclude registration of natural radiation events, including cosmic one (muons, cosmic neutrons);
- Both active and passive protection should be used;
- Active protection is an anti-coincidence system including plastic scintillators around neutron detectors;
- In order to provide the accumulation of events continuously, the remote access and automation is required;
- The results of measurements session should be processed promptly to get an information of registered neutrons multiplicities;

Detectors system

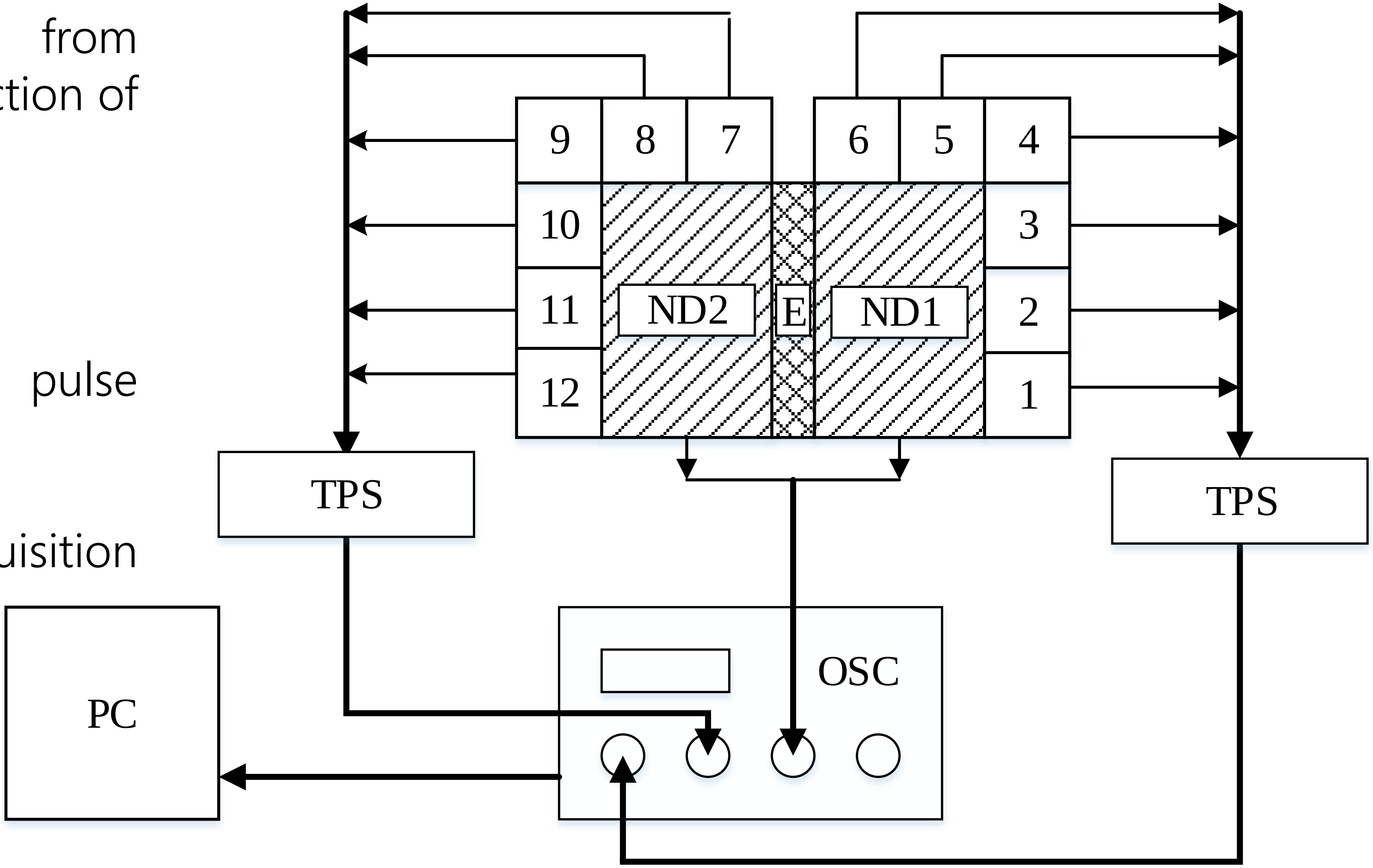
- Arrangement of two ^{3}He detectors with efficiency $\varepsilon=0.31$ in geometry shown below (by measurements with ^{252}Cf source);
- Source of neutron clusters is enriched UO_3 (90% ^{235}U, 10% ^{238}U) powder (m = 5.5 g) placed uniformly on flat holder;
- Emitter is placed between two detectors;
- 12 plastic scintillators are placed around neutron detectors and used as trigger for anticoincidence signal;

Experimental unit:
ND – neutron detectors;
(1-12) – plastic scintillators;
E – neutron clusters emitter



Experimental unit connection diagram

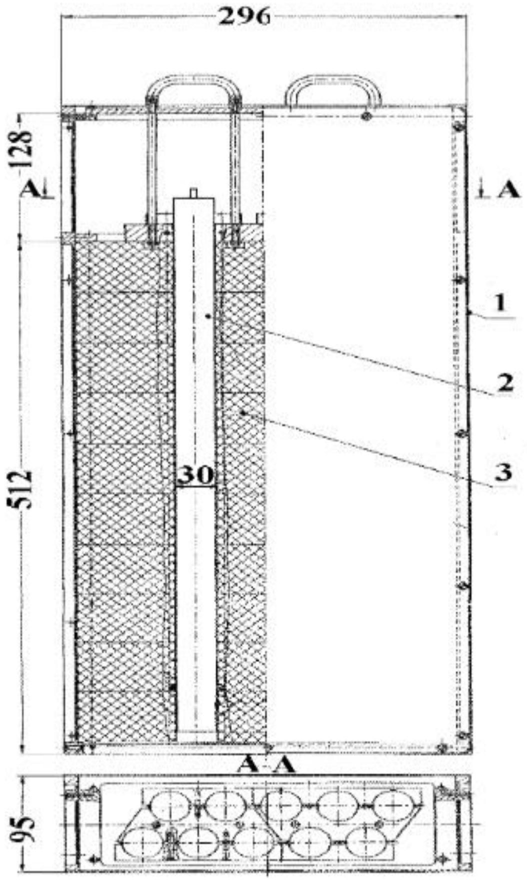
Connection diagram. Data from detectors is transferred in direction of arrows:
ND – neutron detectors;
(1-12) – plastic scintillators;
E – neutron clusters emitter;
TPS – 6 channel threshold pulse shaper with 100 μs delay;
OSC – digital oscilloscope;
PC – computer with data acquisition software



TPS is necessary to delay anticoincidence signal from scintillators!

Neutron detectors

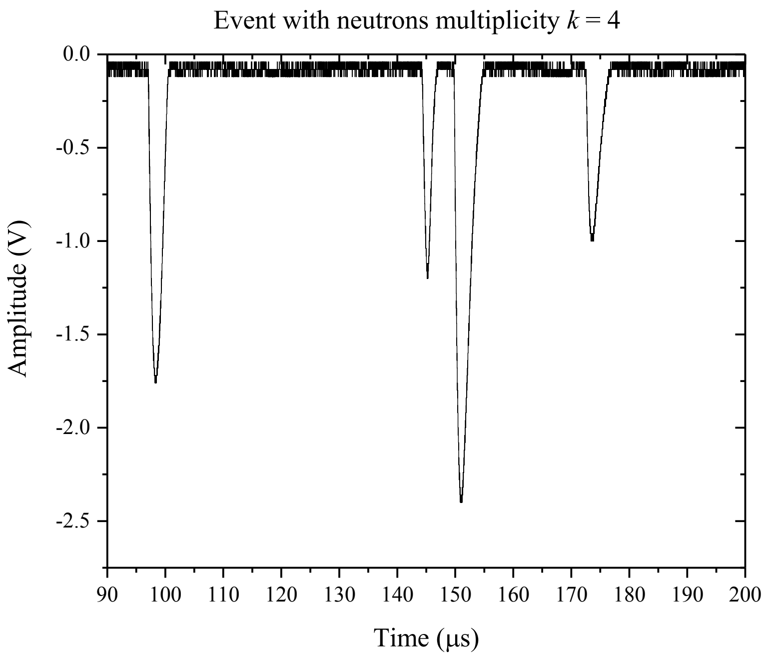
- 2 detectors, each is containing 10 ^{3}He-filled counter tubes placed in polyethylene moderator; working principle is based on registration of ^{3}He(n, p)^{3}H reaction products;
- ^{3}He(n, p)^{3}H reaction cross-section for thermal neutrons is σ=5400 b;
- Additional polyethylene moderator plates with different thickness are placed in Al casing - neutrons detection efficiency depends on thickness of moderator plates [6];
- Average lifetime of fast neutron in this detector is 55 μs [6];
- To register multiple neutrons we accumulate events within 100 μs after trigger signal;
- Greatest part of neutron lifetime is its drift in moderator and counter tubes after thermalization [6];
- Average signal duration is 4 μs

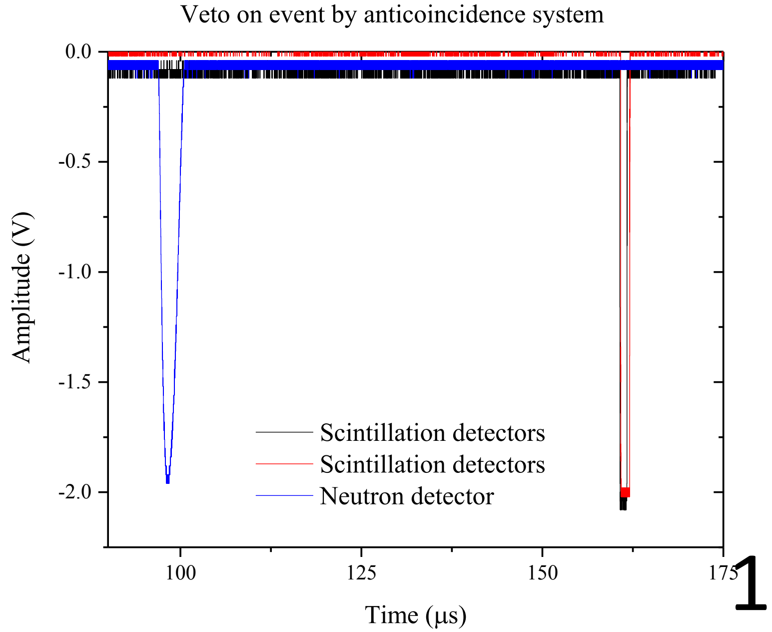


Schematic view on neutron detector's inner parts:
- unfilled cylinders are counter tubes;
- shaded is the moderator

Protection from background influence

- Cosmic muons ($120\ \frac{muon}{m^2 \cdot s}$) and neutrons ($1\ \frac{neutron}{m^2 \cdot s}$) at Tomsk latitude with energies around GeVs
- Background events affect the final results;
- Previous studies [3, 5] had lack of background protection;
- We must distinguish signal from emitter and cosmic radiation;
- In our experiment we have both passive (unit is placed underground) and active (anticoincidence system) protection;
- Anticoincidence rejects events, if the signal was registered from scintillators in addition to neutron detectors;
- Signal from scintillators is delayed due to high neutron detectors signal duration and high neutron lifetime in detector;



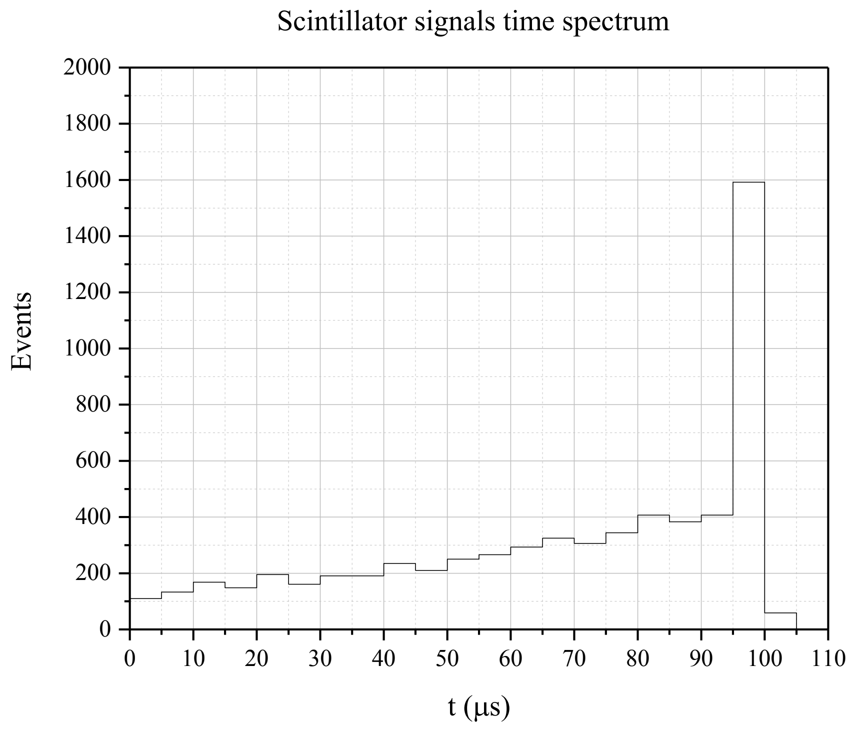


Top: signal of neutrons with multiplicity $k = 4$;
Bottom: signal is rejected due to coincidence with scintillators signal – possibly a muon

5. V.M. Bystritsky et al., Nucl. Instrum. Methods Phys. Res. A834, 164 (2016)

Data processing

- The data from working sessions is promptly processed by software;
- Operator gets information about the number of registered and rejected events, multiplicities of neutrons;
- In addition, energy spectra of neutrons and time spectra of delayed signals from scintillators are provided;
- Operator may control experimental unit remotely, turning on and off hardware using mobile application;
- Remote access to experimental data is also included



Time spectrum of delayed signals from scintillation detectors. Peak around +100 μs is caused by muons registration signal

Results discussion

- The experimental unit was created to search for neutron clusters in heavy nuclei decay;
- Used detectors have high efficiency of neutrons detection and high selectivity of registration;
- Active protection from background radiation improves accuracy of obtained results;
- Remote access to the data and hardware control allows to rapidly control the situation and accumulate bigger amount of data;
- Unit configuration is still improving; at this moment the amount of collected data is insufficient to make conclusions.

Photo of the experimental unit

References

1. F. Miguel Marqués Eur. Phys. J. Plus **136**, 594 (2021)
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6. В.Ф. Борейко, В.М. Быстрицкий, Я. Возняк и др. Препринт ОИЯИ Д15-2001-145, Дубна 2001, 3He – детекторы в экспериментах на мощных импульсных ускорителях.

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