Proceedings of ISINN-29, JINR, E3-2023-58, Dubna, 2023, p.204 –209

Computer Simulation PFN Transport in Neutron Detector

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This work reports results of prompt fission neutron (PFN) emission process simulation of IREN source of resonance neutron induced fission of U-235 using special computer code, developed by authors. The fast neutron detector consisted of 32 liquid scintillation neutron detectors manufactured by SIONICS (Netherland) company. Beam of resonance neutrons produced by IREN facility of Joint Institute for Nuclear Research (JINR) irradiated double Frisch gridded ionization chamber (DFGIC) with uranium target located on the common cathode. PFNs produced in target will be detected by multi-module set of 32 liquid scintillator filled neutron detection modules. In the planned experiments beam of resonance neutrons from the IREN source would irradiate the uranium target of DFGIC, producing fission fragments and PFN. The fast neutron detectors are able to detect PFN and separate the PFN from the background gamma radiation using pulse shape analysis method. For each fission event the following information should be recorded: time stamp of event, fission fragments (FFs) emission angles in respect to the selected coordinate system, FFs pulse heights, and the PFN pulse shape information. The multi-modular structure of PFN detector has the advantage due to higher neutron registration efficiency from the one hand, and the drawback due to the cross-talks between adjacent modules. That effect can produce systematic uncertainty to the multiplicity of the final results. In this work the effect of cross-talks was evaluated using numerical simulation of PFN transport and were taken into account in the final results.

Introduction

Investigation of PFN properties is important in studies of nuclear fission process, due to PFN are carry information on excitation energies of fissile nuclei [1]. For detailed study mass and kinetic energy (MKE) distributions of fission fragments and PFN emission in reactions $^{235}U(n_{res},f)$, $^{237}Np(n_{res},f)$, and $^{239}Pu(n_{res},f)$ induced by resonance neutrons, and in spontaneous fission of $^{252}Cf(sf)$, the neutron detector was manufactured and located in the resonance neutron beam line (flight path length ~9.2m) of IBR30. For detailed study MKE distributions of fission fragments and process of PFN emission in fission of ^{235}U, ^{237}Np and ^{239}Pu nuclei, induced by resonance neutrons and in spontaneous fission of ^{252}Cf, neutron detector (ND) was developed and located at beam line of IREN source in JINR (flight path length ~9.2 m). ND consist of two shoulders contained 16 neutron detecting modules each. The modules are aluminum cylinders with diameter of 80 mm and the height 50 mm filled with scintillating liquid BC501. The modules have transparent for light window to which PMT was glued. The modules were located on the four circles made as cross sections of virtual sphere with radius of 0.5 m: 12 modules were located at two sections with diameters of

30 cm and the rest 20 at two sections with diameter D=450 mm (Figs.1,2). The full angle, covered by the PFN modules was 5.12% of 4π.

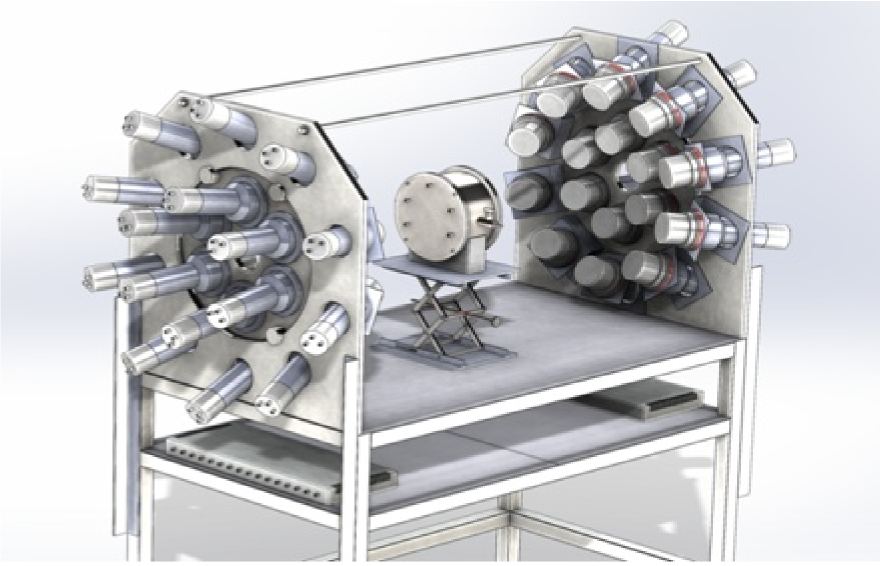

Fig. 1. Photo of neutron detector along with ionisation chamber.

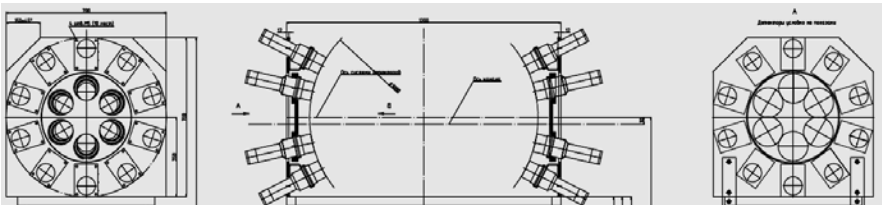

Fig. 2. Schematical view of neutron detector.

The target was made of 1 μm thin organic film with vacuum evaporated gold of ~50 μг /cм^{2}and ^{235}U (of 0.99999 purity) with 70 μг /cм^{2}onto one of its surfaces. The target diameter was 70 mm, and it was mounted on the center of common cathode hole. When the neutron captured by U nucleus, the fission fragments are detected in two separate ionization chambers composing the double ionization chamber filled with P10 gas mixture flowing (20 ml/min) through the chamber, working under normal conditions. The chamber able to measure polar and azimuth angles of fission fragments. Special software was developed for data analysis and data acquisition of fission fragments induced signals.

PFN detecting module

PFN detecting module was made of aluminum cylinder having diameter 80 mm and height 50 mm. Module was filled with BC-501scintillation liquid. The PMT tube was glued to transparent side of the cylinder and was used to amplify the signals (light sparks), generated when PFN collided with molecules of BC-501. PFN caused pulses were amplified by PMT and analyzed in data acquisition software to separate PFN from gamma radiation using pulse shape analysis. The PMT pulse was accepted by data acquisition software if its kinetic energy exceeds the 0.15 MeV level. To track the trajectory of the PFN from the origin point inside the neutron detector to the point, where neutron was captured, or leave the detector volume, a special software code was developed, using Monte Karlo method [3,4]. The following original conditions were assumed: PFN was emitted from the random point of the target, it had randomly selected launching angle in respect to the target plane. The kinetic energy value was distributed according to Maxwell low, as in the following formula:

$$F(E_0) = \frac{2\pi}{\sqrt{(\pi kT)^3}} \cdot \sqrt{E_0} \cdot e^{\frac{E_0}{kT}},$$

where $kT = 1.0 MeV, k$ – is Boltsman constant, and T– is the target temperature.

Trajectory parameters and kinetic energy value were traced from the emission point to the point, where the neutron leave the system or was captured in scintillator volume or its kinetic energy value decrease to the level below $10^{-5} MeV$.

PFN interactions inside the scintillator volume

Liquid BC-501 has the chemical formula CH_2O. Assuming two types of reactions with scintillator molecule: elastic scattering or capture of PFN by one of the atoms of scintillator, the following identifiers were used:

$\sigma_C^{elastic}(E), \sigma_H^{elastic}(E), \sigma_O^{elastic}(E), \sigma_{CH_2O}^{elastic}(E)$– the elastic scattering reaction cross-section of PFN with kinetic energy value E with the atoms: C, H, O, and with molecule CH_2O respectively.

$\sigma_C^{capture}(E) \sigma_H^{capture}(E), \sigma_O^{capture}(E), \sigma_{CH_2O}^{capture}(E)$– the capture reaction cross-section of PFN with kinetic energy value E with atomsC, H, O and molecule CH_2O respectively.

$\sigma_C^{total}(E), \sigma_H^{total}(E), \sigma_O^{total}(E), \sigma_{CH_2O}^{total}(E)$–the total cross-section of interaction of PFN with kinetic energy value E with the atoms C, H, O, or molecule CH_2O respectively.

Let X- is the X free path thin of PFN with kinetic energy value E inside the scintillation liquid. Assuming simulated X has exponential distribution with the following probability density:

$$p(X = x) = \lambda \cdot e^{-\lambda x},$$

where

$$\lambda = N \cdot \sigma_{CH_2O}^{total}(E),$$

$$\sigma_{CH_2O}^{total}(E) = \sigma_C^{total}(E) + 2 \cdot \sigma_H^{total}(E) + \sigma_O^{total}(E),$$

N– is the number of molecules in 1 см^3 of scintillator volume. Scintillation liquid formula is CH_2O, its density is$\rho = 0{,}815 \ {}^{g}/_{cm^3}$. Neglecting binding energy, we find atomic weigh of CH_2O is 30,02109 as

$$N = \frac{6{,}0221408 \cdot 10^{23} \cdot 10^3 \cdot 815}{30{,}022109} = 163{,}4866 \cdot 10^{20} \text{molecules}.$$

Probability of reaction between PFN and atom of scintillator $\rho_C^{total}(E), \rho_H^{total}(E)$ и $\rho_O^{total}(E)$ are proportional to corresponding cross-sections, taking into account the multiplicity of atoms in the molecules of the scintillator as

$$\rho_C^{total}(E)/\rho_H^{total}(E)/\rho_O^{total}(E) = \sigma_C^{total}(E)/2 \cdot \sigma_H^{total}(E)/\sigma_O^{total}(E).$$

Probability of type of interactions between neutron and selected atom of molecule of scintillator is proportional to respective cross-sections:

$$\rho_{atom}^{capture}(E)/\rho_{atom}^{elasic}(E) = \sigma_{atom}^{capture}(E)/\sigma_{atom}^{elastic}(E), atom = C, H, O.$$

Interaction between PFN and atom leads to kinetic energy loss of the particle. Full energy obtained by material of scintillator module from the moving neutron was calculated as sum of energy release in elastic collisions of neutrons with hydrogen atoms and in the neutron capture by the atom of scintillator. The module generates a signal when the energy transferred to the material of scintillator was higher than the threshold value:

$$E_{modul} > 0.15\ Mev.$$

Results of simulation

The goal of this work was to estimate the share of multiple scatterings (2,3,4,5) of the given particle at the atoms of the medium. Multiple scattering of the neutrons inside the neutron detector could imitate false multiplicity. In this connection it was necessary to estimate the share of such multiple scattering using computer simulation of the transport of neutrons inside the detector volume. We have developed computer code, generated 20 scenarios of PFN emission causing signals in a given detector. Results obtained in simulation process presented in Table with the following identifiers:

R – serial number of the scenario;

N_R^i - the number of neutrons detected in scenario R in I modules;

$N_R^{\geq 5}$- the number of neutrons detected in scenario R in 5 or more modules;

N_R^{real}–the real number of neutrons, registered by system in scenario R:

$$N_R^{real} = \sum_{i=1}^{\infty} N_R^i\,;$$

$N_R^{visible}$ –the number of sparks, registered by ND in scenario R:

$$N_R^{visible} = \sum_{i=1}^{\infty} N_R^i \cdot i\,;$$

ε_R - is the systematic relative error in measurement of number of neutrons in scenario R

$$\varepsilon_R = \frac{N_R^{visible} - N_R^{real}}{N_R^{visible}}.$$

As $N_R^{\geq 5} = 0$ for all R, so

$$N_R^{real} = \sum_{i=1}^{4} N_R^i\,;$$

$$N_R^{visible} = \sum_{i=1}^{4} N_R^i \cdot i.$$

R	N_R^1	N_R^2	N_R^3	N_R^4	$N_R^{\geq 5}$	N_R^{real}	$N_R^{visible}$	ε_R
1	19169	1055	25	0	0	20249	21354	0.052
2	19281	1108	25	0	0	20414	21572	0.054
3	19290	1071	34	0	0	20395	21534	0.053
4	19032	1058	29	1	0	20120	21239	0.053
5	19102	1120	33	0	0	20255	21441	0.055
6	19288	1069	31	0	0	20388	21519	0.053
7	19087	1114	27	0	0	20228	21396	0.055
8	19215	1102	23	0	0	20340	21488	0.053
9	19092	1149	28	0	0	20269	21474	0.056
10	19161	1089	32	0	0	20282	21435	0.054
11	19396	1081	19	0	0	20496	21615	0.052
12	19180	1140	29	1	0	20350	21551	0.056
13	19106	1104	16	1	0	20227	21366	0.053
14	19152	1072	33	1	0	20258	21399	0.053
15	19173	1105	31	0	0	20309	21476	0.054
16	19256	1078	20	0	0	20354	21472	0.052
17	19171	1145	22	0	0	20338	21527	0.055
18	19049	1125	31	2	0	20207	21400	0.056
19	18938	1110	26	0	0	20074	21236	0.055
20	19096	1110	28	0	0	20234	21400	0.054

Table. Results of simulation neutron transport in ND

Conclusion

In this investigation of PFN registration using detector, consisting of 32 BC501 liquid filled scintillator modules was done. Detectors have the ability to separate neutrons from prompt gamma radiation using pulse shape analysis. Computer simulation of neutron transport inside the detector body was done along with estimation of systematic errors caused by multiple scattering of neutrons. Statistical accuracy of simulation was estimated to be less than 5%:

$$N_R^{real} \approx 0{,}95 \cdot N_R^{visible}.$$

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