Powerful Nanosecond Single-Shot Technique for Detection of Illicit Materials and Explosives

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INTRODUCTION

The terrorists' attacks on civil objects throughout the world are well known

Traffic of explosives by vehicles in a luggage and on human bodies on the ground, by sea and air inside a country, as well as to and from abroad, is of an earnest concern

All of these facts demand elaboration of fast and efficient methods of screening suspicious objects

Methods using fast neutrons may give the necessary solution

They use isotope sources, classical neutron generators and accelerators and X-Ray tubes as sources of penetrating radiations

Between their problems the most important ones are *a **high level of dose*** needed for identification of materials (current neutron-based technologies require a total neutron yield within the limits 10^10…10^13 neutrons per an interrogation of a single item of the airport luggage) and *a **low signal-to-noise** ratio at the detection part* of the systems

Both problems result in a necessity ***to produce many shots*** with the above generator-based neutron sources (~10^6...10^8 pulses) and consequently in ***a long interrogation time*** and in a quite high ***activation of the objects*** under unveiling

Thus the main goal cannot be considered up to now as perfectly resolved

Our method belongs to the wider group of approaches that makes use an ***interaction of fast neutrons with different materials***

As a result of such interaction ***a field of scattered neutrons*** is formed

The field appears because of ***elastic*** and ***inelastic*** scattering of primary neutrons by nuclei of the irradiated matter; besides an ***induced gamma radiation*** is emitted from an object under irradiation

Information on elemental composition of the object can be obtained from ***spectrum*** of both the gamma radiation and the scattered neutrons

Simultaneously due ***to hard X-Rays*** generated by our device in the same shot we shall have an ***X-Ray image*** of an object under interrogation

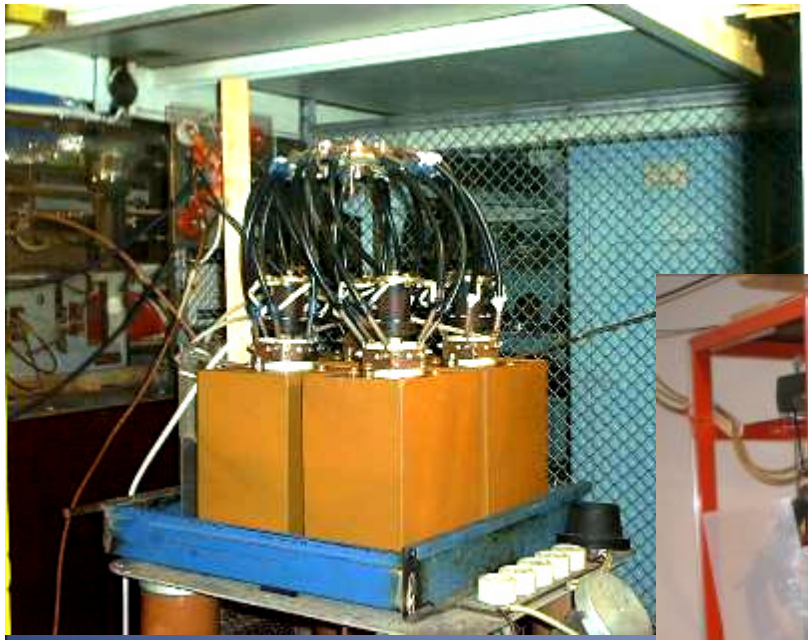
Compared to the so-called ***Fast Neutron Scattering Analysis*** developed lately by Buffler et al. we proposed to bring into play a neutron source based on a ***plasma accelerator*** of the Dense Plasma Focus type ***(DPF)*** generating ***nanosecond (ns)*** pulses of ***neutrons and hard X-Rays (HXR)*** and having *simultaneously* a ***very high intensity*** – up to 10^8…10^12 neutrons and 10…100 J of HXR ***per a single pulse***

These characteristics open a new opportunity for explosives' detection allowing utilization the well-known concept of ***TOF*** measurements and ***HXR*** imaging implemented in a ***single shot*** of the DPF

Equipment

We use ***PF-10*** (ITEP, RF, 10-kJ, deuterium, 3×10^8 n/pulse), ***PF-6*** (IPPLM, Poland, 7.4 kJ, deuterium, 10^9 n/pulse) and ***ING-103*** (VNIIA, RF, 3...10 kJ, deuterium-tritium, 10^10...10^11 n/pulse)

This method will ensure a profound ***decrease of signal/noise ratio***, a minimization of the overall irradiation ***dose by 1-3 orders*** of magnitude and the ***interrogation time by 8-9 orders of magnitude*** compared with existing techniques; it will also result in a ***lower activation*** of items under inspection and in a ***decrease of a false alarm rate***



PF-10 (ITEP)

PF-6 (IPPLM)

ING-103 (VNIIA)

The DPF-based neutron source is ***ecologically more acceptable*** compared with others because it produces a neutron radiation only ***"on demand"*** for a few nanoseconds and it ***doesn't require a special storage***

It uses charging voltage of about ***10 kV***; this modern DPF is characterized by operation with ***vacuum-tight (welded) chambers*** with the life-time of the order of 10^6 "shots"; it has relatively ***low size*** and ***weight*** (0.5…1.0-m^2 footprint and 100-400 kg), comparatively ***low cost***, and it obeys a possibility to work with a ***high repetition rate*** (tested up to 15 cps), etc.

For registration of direct and scattered neutrons as well as hard X-Rays we used PMT+S: Hamamatsu-1949-51 module, S/N WA5952, ***FWHM = 3.12 ns*** and a PMT of the type SNFT with ***FWHM = 2.5 ns***

The method

Main principle of the technique used is based on the change of the energy of scattered neutrons, when their energy ***dissimilar decreases due to elastic scattering on nuclei of various elements*** having *different* masses; it must be reflected in a ***difference of TOF*** of these neutrons

Element's content (chemical formula) of the interrogated substance can be determined afterwards taking into consideration these ***time lags***, the ***amplitudes of the neutron pulses*** scattered by corresponding element's nuclei taking into consideration the ***respective cross-sections*** of the elastic scattering of neutrons on the nuclei of the

Here we shall mention two important results of ***numerical simulations*** made by us with a help of MNCP-5:

1) We understand how to make the ***proper choice for geometry*** and ***distances*** of our scattering experiments

2) We found that the ***number of scattered neutrons at our best geometries is enough*** to be registered by our technique in both cases – ***lower-energy neutrons elastically scattered by stable isotopes of C, N, O, and H***, and ***higher-energy neutrons inelastically scattered by fissile materials***

Experiments

In all experimental sessions we investigated scattering of neutrons by 1-liter bottles of methanol (CH3OH), phosphoric acid (H2PO4) and nitrogen acid (HNO3) positioned in a very close vicinity to the DPF chamber

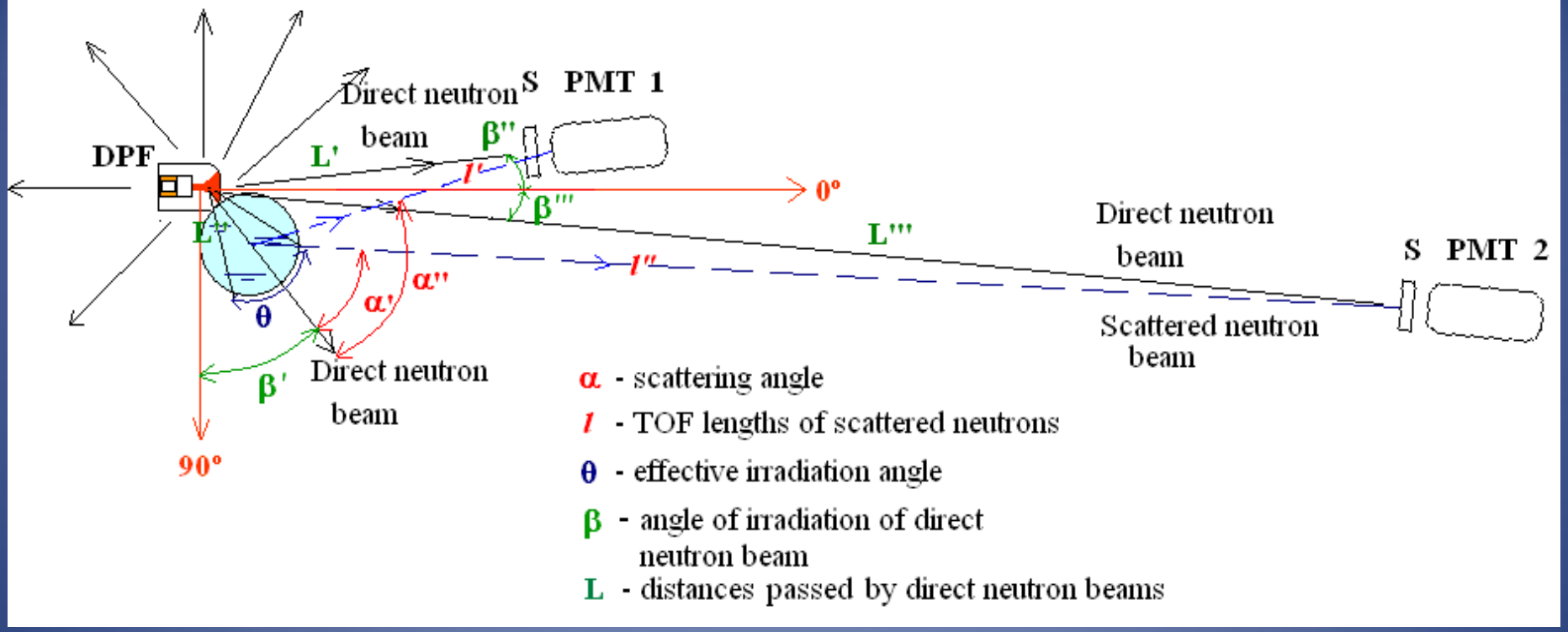
In the first case we operate with the DPF bank energy on the level of about ***7 kJ*** with neutron output of the device ***~10^9*** neutrons per pulse

Our scintillator had diameter and length = 10x10 cm^2

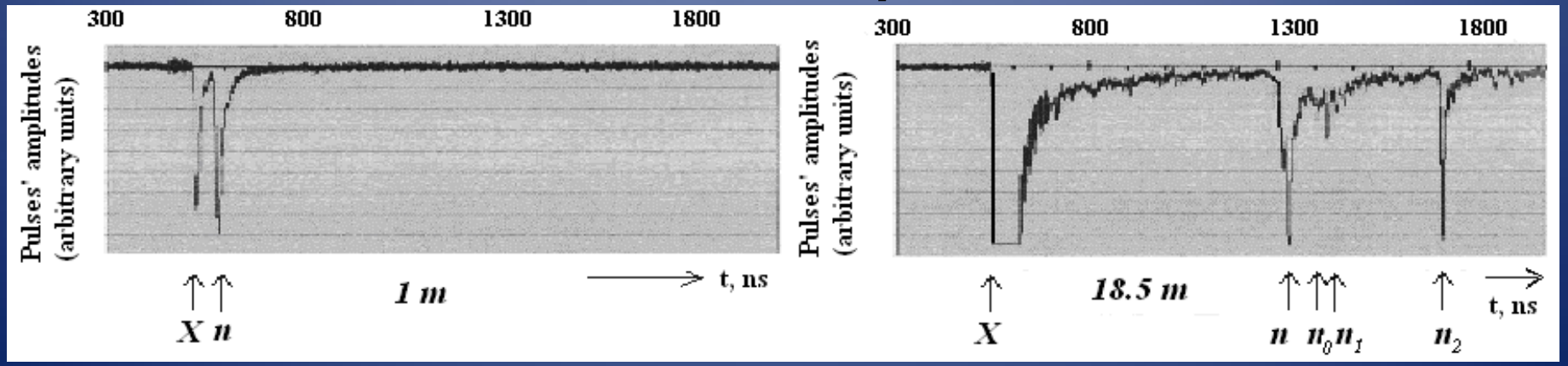
Calculations of neutrons' energy of the neutron pulses by using time-of-flight (TOF) data with the help of formula:

E [MeV] = (L[m] / t [ns])2×5.23·10^3,

have shown in this case that their medial energy is ~ 2.6



Scheme of the experiments



Oscilloscope traces of PMTs placed at 1.0 (a) and 18.5 meters (b) from the target

To calculate the real position of the above neutron pulses on the oscilloscope trace and consequently their TOF and energy we have to perform the following procedures:

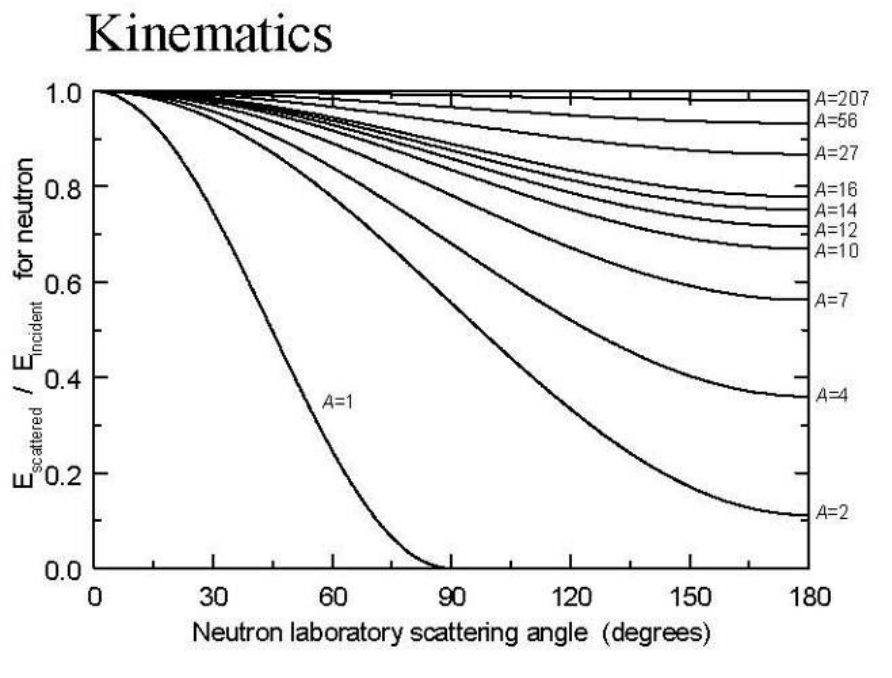
1) **To move *forward*** in time (to the left on the trace) the ***hard X-Ray*** pulse by its TOF of 18.5 m (62 ns) – this will be the moment of the appearance of the front of HXR pulse inside the chamber

2) **To move *backward*** (to the right on the trace) the above point by **8 ns** – this will be the moment for ***neutrons to top out maximum*** inside the chamber.

After the above procedure we shall have the ***reference point*** **("0 ns"),** from which we can calculate all time intervals

From the graphs based on kinematics of the scattering and on our experimental geometry one can see that our two peaks on the oscilloscope trace – "*n*0" (908 - 10 = 898 ns) and "*n*1" (925 - 10 = 915 ns) – may be attributed to the ***scattering of the 2.45-MeV neutrons on the oxygen and carbon nuclei*** accordingly

For the pulse "*n2"* we found that this is our high-pressure 20-l 150 atm. cylinder with deuterium placed at 1 m from the DPF chamber



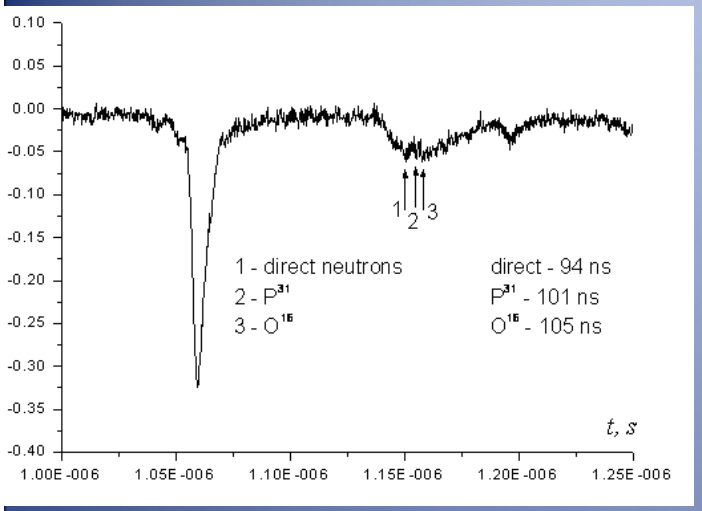
Graph showing the ratio of energy of neutrons scattered by nuclei of various elements to the initial energy of neutrons of the irradiating beam in dependence of scattering angle

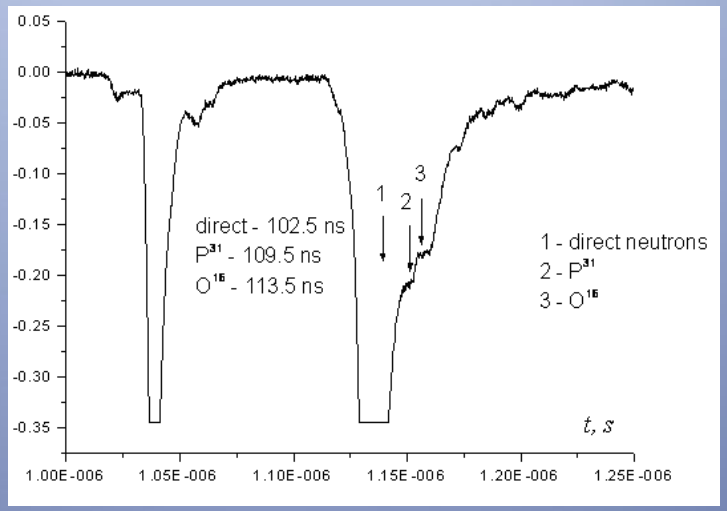
Our 2-nd experiment was devoted to the phosphoric acid (H3PO4) used as a target; it was installed tightly with the DPF chamber with the geometry as follows:

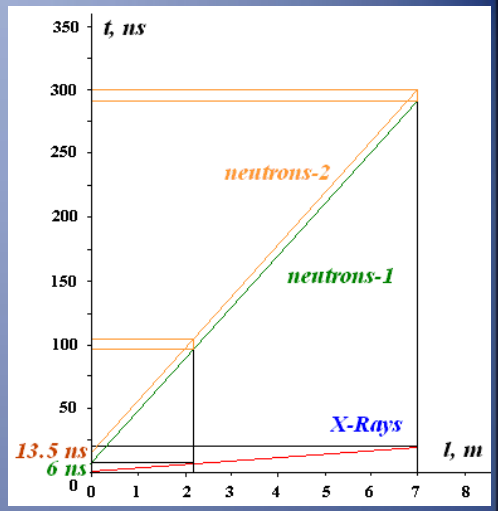
$\beta' \approx 35°$, $\beta'' \approx \beta''' \approx 27°$, $L' = 2.2$ m, $L'' = 8$ cm, $\theta \approx 10°$, $L''' = 7$ m

In these tests we have experienced an opportunity to use much ***lower bank energy (~3 kJ), smaller DPF chamber, and decreased neutron yield (~3×10^8 n/shot)*** what results in ***lower activation of objects*** under interrogation and in ***shorter TOF base (2.2 meters only).*** We used here 2 PMT placed in two different distances from the scatterer

In this case the neutron pulse duration detected at a close vicinity to the DPF chamber became 5-8 ns; thus ***the thickness of an almost spherical neutron "shell" spreading from the source was ~ 10-15 cm***





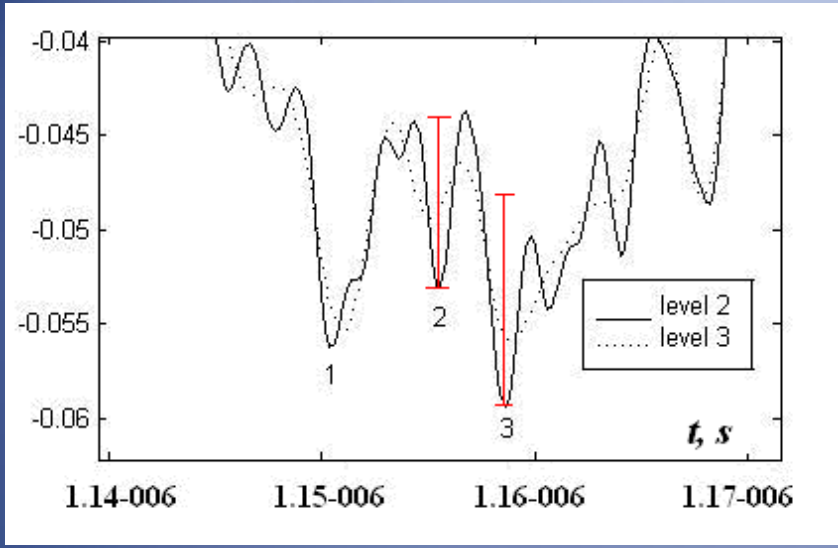


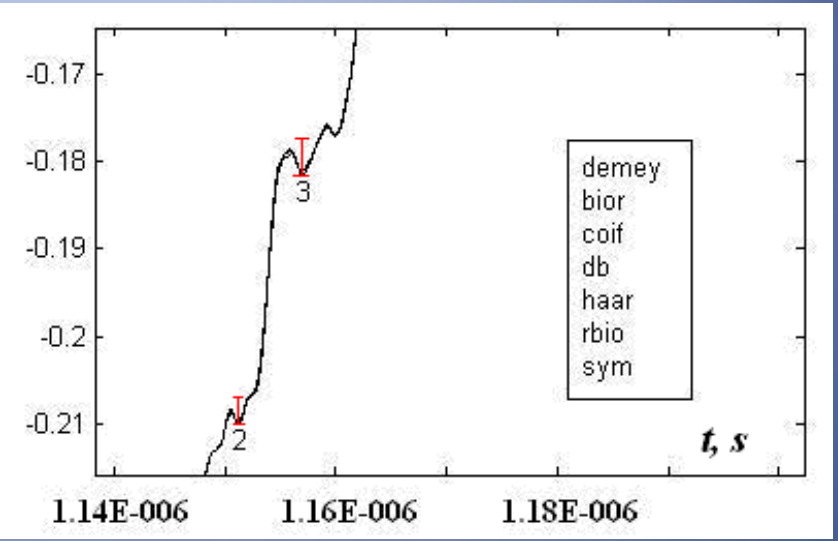
a) b) c)

*Oscilloscope traces with direct beam of neutrons (1) blocked almost completely by a neutron screen (a) and without shielding (b); TOF of X-Ray and neutron pulses at **2.2** and **7.0** meters (c)*

Calculations show that for the experiment of *(a)* we had a time-delay between the X-Ray front and the neutron maximum equal to ***6 ns*** whereas for *(b)* this value was ***13.5 ns***

The neutron detector signals contain an essential noise component in this our case of ***low dose of neutrons***; trying to de-noise these signals, we used wavelet method suggested by MATLAB Wavelet Toolbox





a) *b)*

The above oscilloscope traces where for de-noising the "dmey" wavelet was used

For the particular elements and angles according to kinematics of elastic collisions we have the energy of neutrons scattered on ***O16 nuclei 0.90*** time less in comparison with the initial one whereas for ***P31 nuclei this figure is 0.95***

Using the well-known formula for the neutrons' time-of-flight (TOF) method:

$$En(\text{MeV}) = [72.24\ L\ (\text{m}) / t\ (\text{ns})]^2,$$

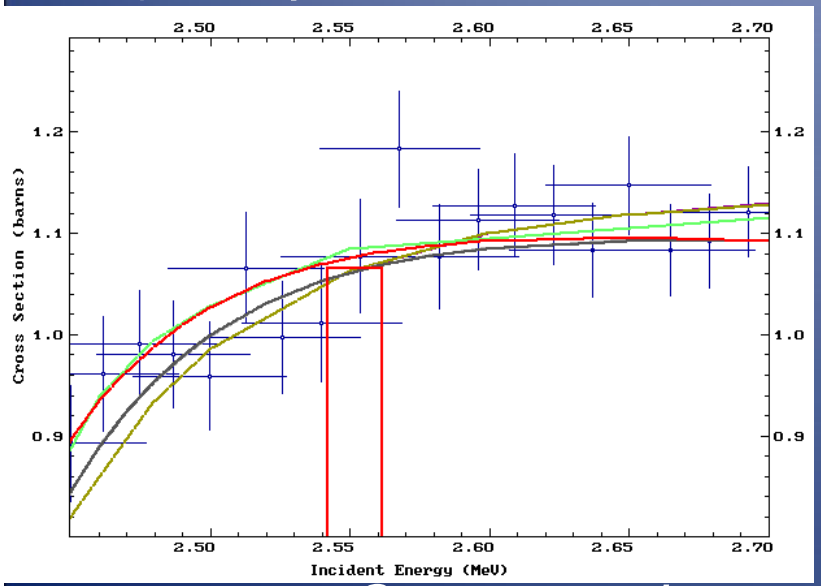
and taking into consideration TOF of 2.55-MeV neutrons from the source to the bottle axis (3.5 ns), TOF of X-Rays for 2.2 m (7 ns) and delay-time of neutrons' peak compared to the X-Rays front (6 and 13.5 ns) one may calculate moments of appearance of *peak 1* (direct neutrons), *peak 2 (neutrons scattered by P31 nuclei)* and *peak 3 (neutrons scattered by O16 nuclei)*

In the above two cases these instants of time should be 96 ns, 101.5 ns, 104.5 ns and 102.5 ns, 109 ns, 112 ns respectively for (*a, b*)

Agreement between experiments and calculations looks very good

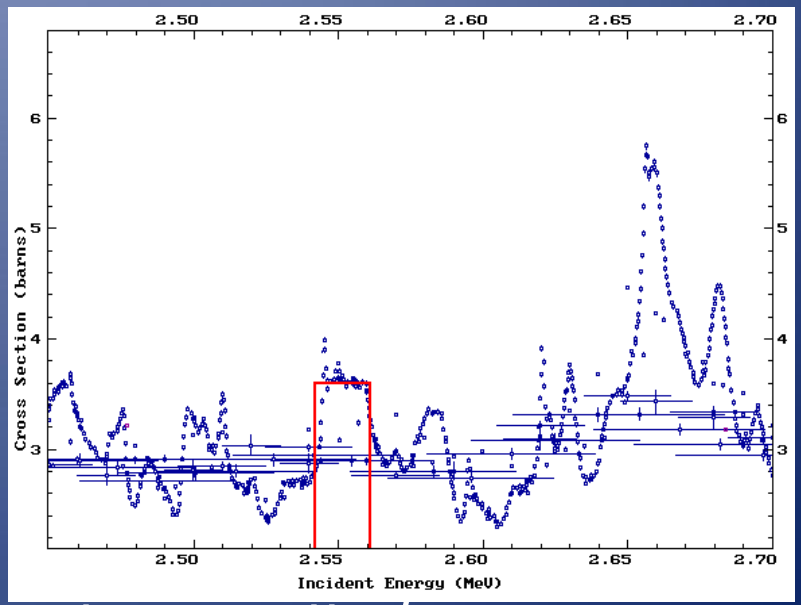
However to be sure that these peaks are really belonged to neutrons scattered by nuclei O16 and P31, contained in the phosphoric acid, we made an analysis of ***relative amplitudes*** *of these peaks*

Cross-sections of elastic scattering of neutrons on these elements in the range 2.45 through 2.7 MeV (i.e. in the range of energies, which corresponds to a change of the angle of the direct neutron beam propagation from the DPF in the relation to its Z-axis) are presented below



a)

b)



Cross-sections of elastic neutron scattering by O^{16} (a) and P^{31} (b) nuclei (2.45-2.70 MeV)

It is clearly seen that for the irradiating beam (<*E*> = 2.55 MeV) the value of the cross-section for ***P31*** is about 3.3 times higher than that for the nuclei of ***O16***

But in a molecule of the phosphoric acid ***the number of oxygen atoms is 4 times higher*** than that for the phosphorus ones (H3PO4)

That is why these both peaks are ***almost equal*** by their amplitudes (difference is 1.2 times)

In the 3-rd case the NINIS experiment was performed with ***14-MeV neutrons*** elastically scattered by a 1-littre bottle of HNO3 acid

Researches were provided with the ***ING-103 device*** operating with the ***D-T mixture*** as a working gas

In this case we may expect the following features distinguishing this experiment from the DPF filled with pure deuterium:

Utilization of the 14-MeV neutrons will result in a ***decrease*** of the time-of-flight ***(TOF)*** of 14-MeV neutrons – and hence in a corresponding ***lower*** **separation of pulses** of *scattered* neutrons from different elements – ***by a factor of 0.4***; it will demand an ***increase*** in the corresponding ***TOF base*** in this case by the ***2.5*** times, which ***decreases*** the number of registered scattered neutrons by a factor ***6.25***

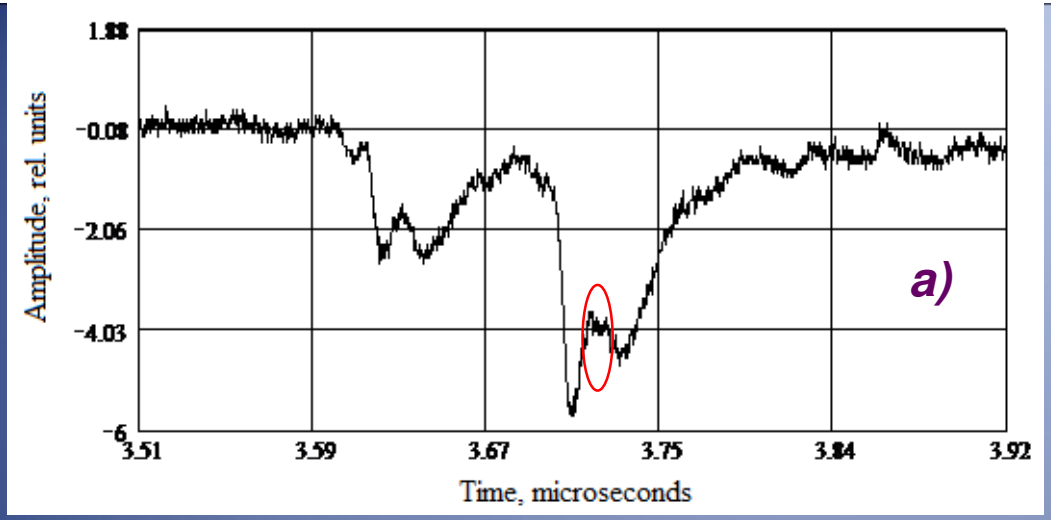
Cross-sections of elastic scattering of 14-MeV neutrons by nuclei of ***carbon, nitrogen and oxygen*** (the elements usually presented in explosives) are **less by 1.5-3 times**

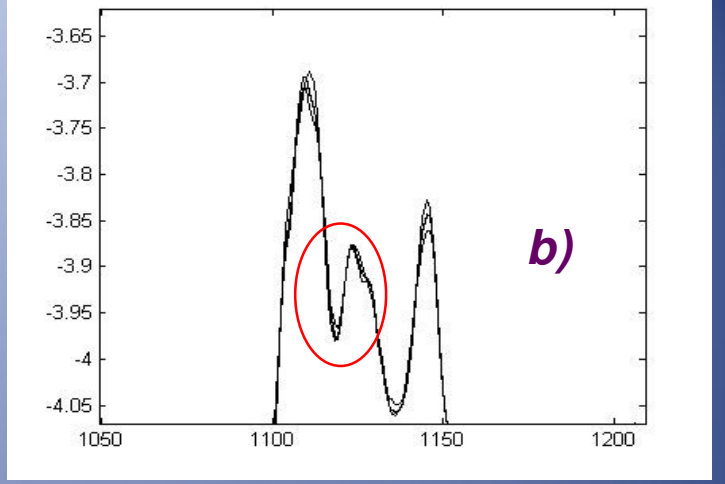
However the ***neutron yield magnitude of a DPF grows in this case by one hundred times***. So we shall obtain a **5-10-times benefit in the scattering signals' gain**

Neutron energy equal to 14 MeV is well ***above a number of thresholds of nuclear reactions*** of neutrons with substances under the interest – oxygen, nitrogen, carbon, hydrogen, etc.

Appearance of ***characteristic γ-rays*** produced during *an inelastic scattering of 14-MeV neutrons* provides ***additional information***, which is important for the unveiling procedure

Input (original) oscilloscope trace at the position of the peak of scattered neutrons and the same trace after wavelet processing on the level 2 are shown below





1) Positions in the oscilloscope traces of the neutron pulses ***scattered by nitrogen and oxygen nuclei coincide with those calculated for the geometry and distances*** of our experiment (for PMT+S_1 by 6.0-6.5 ns and for PMT+S_2 by 9.5-10.5 ns later in relation to the peak of direct neutrons correspondingly)
2) ***The distance from the scatterer to the PMT+S_2 chosen for the experiment (544 cm) is not enough large for separation*** of groups of neutrons scattered by nuclei of nitrogen and of oxygen (about 1 ns here) for the neutron pulse duration (approximately 20 ns) generated by our DPF chamber in these two shots (must be about 12 meters instead of 5.5 m)

Conclusion

Due to these experiments it becomes clear that ***NINIS technique*** can be applied in many cases of interrogation of unknown objects, in particular when their size and shape is compared with the space occupied by DPF neutron pulse

Further computer simulations and experiments must be provided for better understanding of limits and restrictions of the method as well as for application of it to interrogation of lengthy objects and fissile materials

Acknowledgements

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