



Scientific Workshop on Nuclear Fission dynamics and the Emission of Prompt Neutrons and Gamma Rays, THEORY-3

TANGRA-Setup for the Investigation of Nuclear Fission induced by 14.1 MeV neutrons

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Abstract

The new experimental setup TANGRA (Tagged Neutrons & Gamma Rays), for the investigation of neutron induced nuclear reactions, e.g. (n, xn') , $(n, xn'\gamma)$, (n, γ) , (n, f) , on a number of important isotopes for nuclear science and engineering ($^{235,238}\text{U}$, ^{237}Np , ^{239}Pu , $^{244,245,248}\text{Cm}$) is under construction and being tested at the Frank Laboratory of Neutron Physics (FLNP) of the Joint Institute for Nuclear Research (JINR) in Dubna.

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The TANGRA setup consists of: a portable neutron generator ING-27, with a 64-pixel Si charge-particle detector incorporated into its vacuum chamber for registering of α -particles formed in the $T(d, n)^4He$ reaction, as a source of 14.1 MeV steady-state neutrons radiation with an intensity of $\sim 5 \times 10^7$ n/s; a combined iron (Fe), borated polyethylene (BPE) and lead (Pb) compact shielding-collimator; a reconfigurable multi-detector (neutron plus gamma ray detecting system); a fast computer with 2 (x16 channels) PCI-E 100 MHz ADC cards for data acquisition and hard disk storage; Linux ROOT data acquisition, visualization and analysis software. The signals from the α -particle detector are used to 'tag' the neutrons with the coincident α -particles. Counting the coincidences between the α -particle and the reaction-product detectors in a 20ns time-interval improves the effect/background-ratio by a factor of ~ 200 as well as the accuracy in the neutron flux determination, which decreases noticeably the overall experimental data uncertainty.

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Peer-review under responsibility of the European Commission, Joint Research Centre – Institute for Reference Materials and Measurements

Keywords: Neutron Induced Nuclear Reactions; Standard Nuclear Reactions; Time-correlated Associated Particle Method

1. Introduction

Nuclear data are of fundamental importance in nuclear technology studies such as the design of fission power plants, fusion devices and accelerators for medical applications. Large amounts of data required are stored in computer readable formats in data libraries and include the general purpose files used for neutronics calculations.

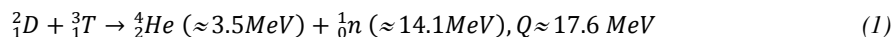
Measurements of neutron induced reaction cross sections (CS) can be simplified, if they are measured relative to so-called neutron cross section working standards (CSWS), for which the reaction cross sections are known with the highest precision. Cross-section standards provide a characterization of the neutron fluence incident upon the sample under investigation. That is why a permanent effort is made to improve the quality of the standards' nuclear reaction data using different measurement techniques (Collona, 2009; Carlson, 2011; Forrest, 2011).

In fast-neutron induced reaction three principal methods are used for determining the absolute neutron flux: 1) the associated particle (AP) method (Okhuysen et al., 1958); 2) the bath method (Mien-Wu et al., 1973) and 3) the standard cross section (SCS) method. In practice, the neutron-induced fission CS of heavy nuclei is measured relative to the CS of the reaction $^{235}U(n,f)$ for neutrons with energy $E_n \leq 1$ MeV and relative to the reaction $^{238}U(n,f)$ for $E_n > 1$ MeV neutrons. In the past, the time-correlated associated particle (TCAP) method has already been used by (Adamov et al., 1980; Arlt et al., 1980; Mahdavi et al., 1982) to absolutely measure the $^{235}U(n,f)$ and $^{238}U(n,f)$ reaction cross sections for neutrons with $E_n = 14.2$ MeV and 14.7 MeV (Li et al., 1986), for $E_n = 1.9$ MeV and 2.4 MeV (Kalinin et al., 1988), and $E_n = 2 - 20$ MeV (Merla et al., 1992) and on ^{239}Pu (Mahdavi et al., 1982; Merla et al., 1992).

2. Time-correlated associated particle (TCAP) method

The Deuterium-Tritium (D-T) reaction is one of the most important nuclear fusion reaction, because it has the lowest Coulomb barrier (~ 70 keV) and the highest cross section (~ 5 barn) to occur. In addition to its importance for fusion reactor studies, it is used as a source of high energy neutrons for experimental research in fundamental and applied fast neutron induced nuclear reactions.

In a neutron generator ~ 14 MeV D-T neutrons are produced via Eq. (1) when detainees are accelerated to an energy of less than 100 keV and focused on a thin 3H -enriched Ti target (TiT).



Since the α -particle is ‘associated’ with the neutron via the nuclear reaction kinematics, both particles are emitted nearly in opposite direction in the center-of-mass system (CMS) of the reaction. This way, the emission angle of the alpha-particle ‘tags’ the emission angle of the neutron, and its detection starts the measurement ‘timer’ (see sketch in the left part of Fig. 1). The tagged neutron could induce a nuclear reaction of interests (elastic or inelastic neutron scattering, neutron capture, fission or spallation of a nucleus). The products of a particular reaction (scattered neutron, gamma-quanta, nuclear fragments) when registered stops the timer, determining the neutron time-of-flight (and neutron flight distance) from the point of the neutron origin to the point of its interaction with the target nucleus. Measuring the time-correlation between signals from the α -particle and the reaction product, e.g neutron, γ -quantum or fission fragment, it is possible to determine the coordinates of the particular interaction of the ‘tagged’ neutron along its trajectory of propagation through the target. This way becomes possible not only to determine the elemental composition of a target by detecting the characteristic reaction products, but also the voxel dimensions and location in space (cf. left part of Fig. 1).

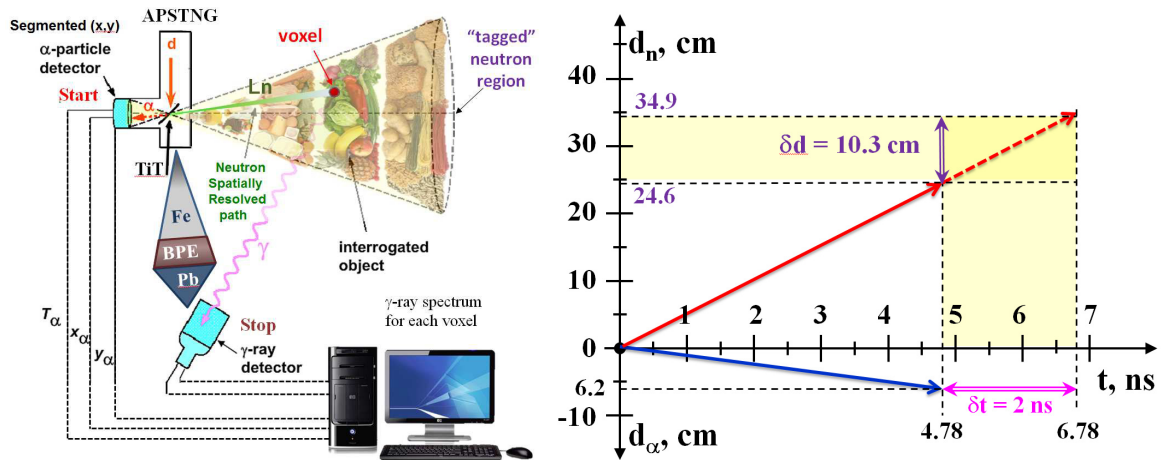


Fig. 1. (a) Scheme of the TCAP-method; (b) Relative distance covered by ‘tagged’ neutron and associated α -particle.

The Fig. 1,b depicts the ideal (α -particle, n) kinematic diagram, which shows the relative distance covered by the 3.5 MeV α -particle and the ‘tagged’ 14.1 MeV neutron following D-T fusion, applied to the ING-27 with the α -sensor 62 mm away from the TiT-target and with a 2 ns timing window for registering the neutron-induced reaction product (e.g. a γ -ray from a neutron inelastic scattering). In such a case the depth resolution of 5-10 cm can be improved only by using faster detectors. Today it is technologically possible to construct low-power, portable, but relatively intense ($\sim 10^8$ neutrons/ 4π) sealed-tube neutron sources for application in scientific research, material science and safeguards as, for example, the one described by (Chichester et al.,2005) or as those neutron (n) generators produced by VNIIA (2014).

Such n-generators in combination with the TCAP method are used to identify explosive in different environments (Bystritsky et al., 2013; Valcovic et al.,2013), to search for diamonds in kimberlite rocks (Aleksakhin et al.,2013) or for detecting special nuclear materials (Carasco et al., 2013).

All about using of the fast neutron generators for analytical purposes can be found in the IAEA Radiation Technology Reports No. 1, 2012.

In measurements of total or differential reaction cross sections and for determining the time-of-flight (TOF) of neutrons that are inelastically scattered from a sample, the TCAP method helps to reduce the uncorrelated radiation background and to improve the quality of the obtained data.

At the Joint Institute for Nuclear Research (JINR), Frank Laboratory of Neutron Physics (FLNP) in Dubna, Russia, the new experimental setup called TANGRA (Tagged Neutrons & Gamma Rays) for the investigation of neutron-induced reactions at $E_n = 14.1$ MeV is under construction and being tested.

Hereunder we will give a brief description of the setup as it will be applied for studying (n, xn') , $(n, xn'\gamma)$, (n, γ) , (n, f) cross sections of high relevance for nuclear science, engineering and technology, ^{235}U and ^{238}U as primary standards and ^{237}Np designated to be a secondary standard.

3. TANGRA experimental setup

The TANGRA-setup consists of a portable neutron generator (ING-27) for producing a continuous beam of 14.1 MeV neutrons, of a compact neutron-gamma shielding-collimator assembly and of an array of NaI (TI), BGO, Stilbene (or Plastic) detectors for gamma-ray and neutron spectroscopy in a variable configuration. TANGRA acquires data with multi-channel, multi-parametric digital data acquisition system (Ruskov et al., 2012).

3.1. Portable neutron generator ING-27

The ING-27 neutron generator (Fig. 2, a) is a new generation computer-controlled portable neutron generators, based on a sealed ($^2\text{H} + ^3\text{H}$) gas-filled neutron tube with a built-in 64-pixel silicon α -particle detector, which was developed at All-Russia Research Institute of Automatics in Moscow (VNIIA, 2014). It is used for remote detection and identification of explosives and other hazardous materials, diamonds in kimberlite, etc., using associated particle imaging (API) methods. The ING-27 provides a continuous neutron flux with an intensity of about 5×10^7 n/s. A compact shielding-collimator assembly made from iron (Fe), borated polyethylene (BPE) and lead (Pb) is used to shape the neutron beam on target and to protect the neutron and γ -ray detectors. Some characteristics of the generator, e.g. neutron fluxes, operation mode and lifetime, are summarized in Tab. 1

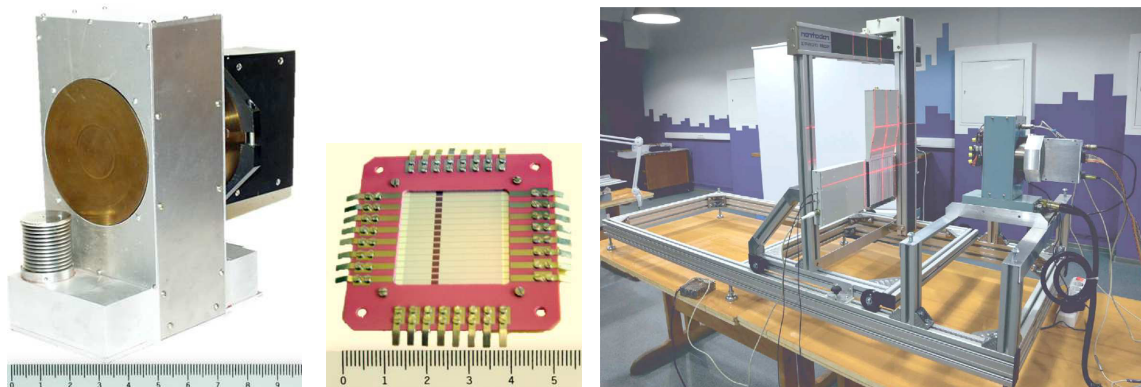


Fig. 2. (a) Portable neutron generator ING-27; (b) 64-pixel Si α -particle detector; (c) JINR fast neutron beam profile-meter

3.2. Alpha-particle detector and tagged fast neutron beam profile-meter

The α -detector incorporated into the ING-27 (Fig. 2,b) consists of 8 mutually perpendicular Si strips on each side, mounted on a plastic frame and forming an 8×8 matrix of 4×4 mm² pixels. The total sensitive area of the 64-element α -detector is 32×32 mm² (Bystritsky et al., 2013). It is located 62 mm away from the centre of the TiT-target. The front-end electronics, which consists of 16 pre-amplifiers, is mounted on the back side of the neutron generator.

Table 1. ING-27 main operating characteristics.

Characteristics	Values
Maximum deuteron energy	80 keV
Maximum Neutron energy (0 deg)	14.802 MeV
Neutron energy (83.9 deg)	14.17 MeV
Minimum Neutron energy (180 deg)	13.326 MeV
Maximum neutron intensity	up to 10^8 n/s
Charged particle (alpha) sensor	Si-planar
Number of pixels	64 (8x8)
Pixel area	4x4 mm ²
Central pixel to target spot distance	62 mm
d-beam Ti-target spot size	4 mm
Target spot to exit windows distance	44 mm
Mode of operation	continuous
DC Power Supply	200 ± 5 V
Maximum power consumption	70 W
Operating lifetime @ 5×10^7 n/s	≈ 1000 h
Operation temperature	10-45 °C
Neutron emission unit (NEU) dimensions	130x279x227 mm
NEU exit steel windows thickness	0.8 mm
NEU weight	8 kg
Power supply and control unit dimensions	351x277x99 mm

To determine the tagged neutron beam location and its profile (width), a Monte-Carlo code, developed by Capote et al. (1990), can help to take into account the space-and-time spread of the tagged neutron beam. Experimentally, the spatial characteristics of 64 tagged fast neutron beams (their location and profiles) can be measured by the scintillation stripped detector setup Profilometer, constructed by JINR Neutron Technology (2014). This relatively small (400x170x40mm) and light (approx. 2 kg) fast neutron profile-meter consists of: 16 polystyrene scintillation bands fed to Bicron BCF-91A light wavelength shifting (WLS) strings with 1 mm in diameter, a 16-channel Hamamatsu H8711-10 PMT and associated electronics. The aperture of the neutron profile-meter is 120×150 mm². At a distance of about 20 cm from the centre of the ING-27 TiT-target the size of each tagged beam in the plane perpendicular to the direction of its propagation is about 13×13 mm.

3.3. n- γ detectors and data acquisition system

A number of NaI(Tl), BGO and Stilbene n- and γ -sensitive detectors are going to be used in different measurements. The recording electronics of the data acquisition system (DAQ), of α - and γ - detector channels, is designed as 2 standard PCI-E boards with 32 inputs and operates in PC direct-memory-access mode. The DAQ includes appropriate software consisting of a basic module (driver), a control program and pulse time-amplitude determination software. The data collection board performs direct digital conversion of signal pulses. The built-in trigger circuits operate in single-channel time and energy modes, and in α - γ coincidence mode. The Linux-based ROOT data analysis framework is used for offline analysis of the data collected in list-mode (Skoy et al., 2014). The same DAQ is supposed to be used in measurements of the fluctuation of γ -ray yields from resonance-neutron induced fission of ²³⁹Pu at IREN TOF neutron spectrometer, as has already been mentioned in Ruskov et al., 2013.

3.4. Detector shielding

In order to determine the proper dimensions of the compact shielding of the detectors against the direct ING-27 neutron beam some experimental work was performed. The complete set of experimental data will be discussed in a separate paper. Here, for a better understanding of the setup, final results will be presented.

In the case of a monolith shielding, iron (Fe) of 40-45 cm thickness can be used because of its relatively high density ($\rho = 7.0 \text{ g/cm}^3$ for low-grade cast and 7.8 g/cm^3 for some steel alloys) and low cost. In iron 14.1 MeV neutrons are losing their energy mainly by inelastic scattering on ^{56}Fe (92% in natural iron) which first excited state is at 847 keV. This has the consequence that the neutrons below this energy are created due to the inefficient energy transfer by means of elastic scattering. Hence, a pure iron shield is not a very efficient shielding at these neutron energies (in the sense of radiation protection), because the quality factor for neutrons as a function of energy has its maximum value at about 500 keV.

To slow the neutrons with intermediate energies down to thermal energies (0.0253 eV), H-containing materials like polyethylene (PE) or PE loaded with boron (BPE) can be used. Pure polyethylene, $(\text{CH}_2)_n$ (H-14% by weight, $\rho \approx 0.92 \text{ g/cm}^3$, flammable) thermalizes neutrons very efficiently, however thermal neutrons can be captured through the $^1\text{H}(n,\gamma)^2\text{H}$ reaction ($\sigma \approx 0.33 \text{ barns}$ @ $E_n = 0.027 \text{ eV}$) by emitting a 2.2 MeV γ -ray, which is difficult to be attenuated, and which gives rise to unwanted background in the γ -ray detectors. To reduce the buildup of those high-energy photons, BPE can be used instead of PE. The thermalized neutrons are captured via the $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction ($\sigma \approx 3837 \text{ barns}$ for thermal neutrons). In about 94% the emitted α -particle is accompanied by a 0.48 MeV γ -ray, with a much shorter attenuation length than the 2.2 MeV γ -ray. Therefore, it can be absorbed by an extra layer of iron or lead (Pb) of appropriate thickness.

A series of neutron radiation transmission measurements have been done to determine the most effective and compact shielding against (n- γ)-radiation of Amcris® hexagonal 78x90x200mm NaI(Tl), cylindrical $\phi 76 \times 65 \text{ mm}$ BGO and $\phi 76 \times 50 \text{ mm}$ Stilbene (DST) detectors. As a result of these experiments, restricting the detector shielding to 50 cm thickness, the optimal attenuation of a mixed (n- γ)-radiation field can be achieved by a sandwich made of Fe(30cm) + BPE(10cm) + Pb(10cm) or Fe(20cm) + BPE(10cm) + Pb(20cm) as depicted in Fig. 3.

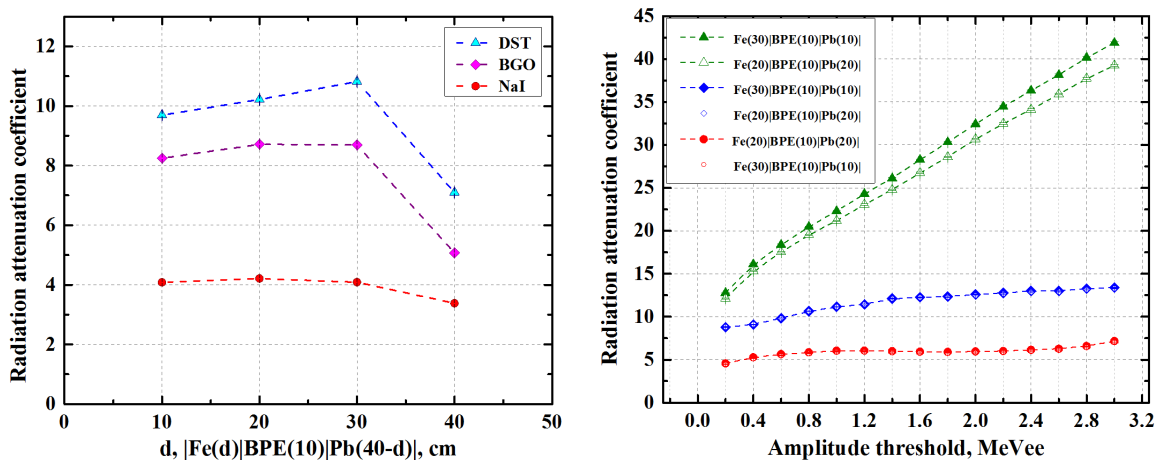


Fig. 3. (a) n- γ attenuation coefficient as a function of shielding composition and detector types; (b) n- γ attenuation coefficient as a function of signal amplitude threshold, equivalent to 1 MeV electron light output (MeVee), for different detectors and two shields.

4. Conclusion

For a future feasibility study of 14.1 MeV neutron-induced reaction cross-section measurements employing the TCAP-method, a new experimental setup was suggested and commissioned at the Frank Laboratory of Neutron

Physics (FLNF) in Dubna. This setup utilizes a portable 14.1 MeV neutron generator ING-27 with an 8×8-channel Si charge-particle detector, incorporated into its vacuum chamber, for registering α -particles associated with the neutrons from the $d(T,n)\alpha$ -reaction. For detecting neutrons and γ -rays from the reaction under investigation a number of NaI(Tl), BGO and Stilbene detectors are under investigation. Optimal protection of the detectors from direct source neutrons as well as from scattered and capture γ -radiation was found to be made of {Fe(30cm) + BPE(10cm) + Pb(10cm)} or {Fe(20cm) + BPE(10cm) + Pb(20cm)}.

Acknowledgements

This work was partially supported by a grant of the Plenipotentiary Representative of Bulgaria at JINR. One of us (I.R.) gratefully acknowledges the support of the EC JRC-IRMM for making it possible to attend this conference as a lecturer.

References

- Adamov, V. M., Alkhozov, I. D., Gusev, S. E., Drapchinsky, L. V., Dushin, V. N., Fomichev, A. V., Kovalenko, S. S., Kostochkin, O. I., Malkin, L. Z., Petrzhak, K. A., Pleskachevsky, L. A., Shpakov, V. I., Arlt, R., Musiol, G., 1980. Absolute Measurements of Induced Fission Cross Sections of Heavy Nuclides for both ^{252}Cf Fission Spectrum Neutrons and 14.7 MeV Neutrons. Nuclear Cross Sections for Technology, Proc. Int. Conf., 22-26 October, 1979, Knoxville, TN. Edited by J.L. Fowler, C.H. Johnson, and C.D. Bowman. US Department of Commerce, National Bureau of Standards, p. 995.
- Aleksakhin V.Yu., Bystritsky V.M., Zamyatin N.I., Zubarev E.V., Krasnoperov A.V., Rapatsky V.L., Rogov Yu.N., Sadovsky A.B., Salamatin A.V., Salmin R.A., Sapozhnikov M.G., Slepnev V.M., Khabarov S.V., Razinkov E.A., Tarasov O.G., Nikitin G.M., 2013. Detection of Diamonds in Kimberlite by the Tagged Neutrons Method. JINR Preprint P18-2013-132, 2013, Dubna, Russia, <http://ntech.jinr.ru/img/papers/almaz-eng.pdf>.
- Arlt, R., Grimm, W., Meiling, W., Krause, R., Ortlepp, R., Teichner, R., Wagner, W., Weidhase, F., 1980. A CAMAC experiment for the precise measurement of the cross section in fast neutron induced fission. Nucl. Instr. and Methods 169, Issue 3, pp. 381-385, <http://www.sciencedirect.com/science/article/pii/0029554X80909325/pdf?md5=a1f62c2712e1369e6547d86319f3bcc&pid=1-s2.0-0029554X80909325-main.pdf>.
- Bystritsky V.M., Zamyatin, N.I., Zubarev, E.V., Rapatsky, V.L., Rogov, Yu.N., Romanov, I.V., Sadovsky, A.B., Salamatin, A.V., Sapozhnikov, M.G., Safonov, M.V., Slepnev, V.M., and Philipov, A.V., 2013. Stationary setup for identifying explosives using the tagged neutron method. Physics of Particles and Nuclei Letters 10 (5), pp. 442–446. <http://ntech.jinr.ru/img/papers/PHPL442.pdf>.
- Capote, R., Monne, G., Sandin, C., Sarria, P., 1990. Energy and time spreads of a particle beam used in APM technique. Nuclear Data Section, IAEA, http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/21/061/21061374.pdf.
- Carlson, A. D., 2011. The neutron cross section standards, evaluations and applications. Metrologia 48, №6, doi:10.1088/0026-1394/48/6/S09, http://iopscience.iop.org/0026-1394/48/6/S09/pdf/0026-1394_48_6_S09.pdf.
- Carasco, C., Deyglun, C., Pérot, B., Eléon, C., Normand, S., Sannié, F., Boudergui, K., Corre, G., Konzdrasovs, V., and Pras, P., 2013. Detection of special nuclear materials with the associate particle technique. AIP Conf. Proc. 1525, 2013, p. 220, doi: 10.1063/1.4802323, <http://dx.doi.org/10.1063/1.4802323>.
- Chichester, D.L., Lemchak, M., Simpson, J.D., 2005. The API 120: A portable neutron generator for the associated particle technique. Nucl. Inst. Methods Phys. Res. B 241(1–4), pp. 753–758, <http://www.thermoscientific.com/en/product/api-120-neutron-generators.html>.
- Colonna, C., 2009. Generation IV nuclear energy systems and the need of accurate nuclear data, 12th Conference on Theoretical Nuclear Physics, IOP Journal of Physics: Conference Series 168, p. 012024, doi:10.1088/1742-6596/168/1/012024. http://iopscience.iop.org/1742-6596/168/1/012024/pdf/1742-6596_168_1_012024.pdf
- Forrest, R.A., 2011. Nuclear Science and Data Needs for Advanced Nuclear Systems, Asian Nuclear Prospects 2010, Energy Procedia 7, pp. 540–552, doi:10.1016/j.egypro.2011.06.075, <http://www.sciencedirect.com/science/article/pii/S1876610211015840>.
- IAEA Radiation Technology Reports No. 1, 2012. Neutron generators for analytical purposes, IAEA, Vienna, ISSN 2225-8833, http://www-pub.iaea.org/MTCD/Publications/PDF/P1535_web.pdf.
- Kalinin, V.A., Kovalenko, S.S., Kuz'min, V.N., Nemilov, Yu.A., Solin, L.M., Shpakov, V.I., 1988. Absolute measurements of the cross section for fission of ^{235}U by 1.9-MeV and 2.4-MeV neutrons using the method of time-correlated associated particles. Soviet Atomic Energy 64(3), pp. 239-244, *Atomnaya Énergiya* 64(3), pp. 194–198, <http://link.springer.com/content/pdf/10.1007%2FBF01123132.pdf>.
- Li, J., Shen, G., Ye Z., Li, A., Zhou Sh., Sun Z., Wu J., Huang T., 1986. 14.2 MeV neutron induced U-235 fission cross section measurement. Inst. of Atomic Energy, Beijing, China, http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/17/081/17081412.pdf.
- Li, J., Zhou, Sh., Liu, W., Ye, Z., Yue, G., Bai, X., 1986. 14.7 MeV neutron induced fission cross section ratio of U-238 to U-235. Inst. of Atomic Energy, P.O.Box 275-60, Beijing, China, http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/17/081/17081413.pdf.
- Mahdavi, M., Knoll, G.F., Robertson, J.C., 1982. Measurements of the 14 MeV Fission Cross-Sections for ^{235}U and ^{239}Pu , Proc. Int. Conf., Antwerp, Belgium, 6–10 Sept. 1982, pp. 58-61.

- Merla, K., Hausch, P., Herbach, C.M., Musiol, G., Pausch, G., Todt, U., Drapchinsky, L.V., Kalinin, V.A., Shpakov, V.I., 1992. Absolute Measurements of Neutron Induced Fission Cross sections of ^{235}U , ^{238}U , ^{237}Np and ^{239}Pu Using the Time Correlated Associated Particle Method (TCAPM), Qaim, S.M. (Eds.). Proc. Int. Conf. on Nuclear Data for Science and Technology, 13-17 May 1992. Jülich, Germany, 1992, pp. 510-513.
- Mien-Win Wu, Jen- Chang Chou, 1973. Absolute Determination of the Fast Neutron Fluxes by Using the Flow-Type Manganese Bath Method, Chinese Journal of Physics 11, No. 2, p. 97.
- Okhuysen, P. L.; Bennett, E. W.; Ashe, J. B.; Millett, W. E., 1958. Detection of Fast Neutrons by the Associated Particle Method. Rev. Sci. Instr. 29, p. 982. <http://dx.doi.org/10.1063/1.1716073>.
- Profilometer, 2014, <http://ntech.jinr.ru/?id=products&content=profilometr>.
- Ruskov, I., Kopatch Yu.N., Pantelev Ts., Skoy, V.R., Shvetsov, V.N., Dermendjiev, E., Janeva, N., Pikelner L.B., Grigoriev Yu.V., Mezentseva Zh.M., Ivanov I., 2012. Prompt Gamma Emission in Resonance Neutron Induced Fission of ^{239}Pu , GAMMA-1 Emission of Prompt Gamma-Rays in Fission and Related Topics, Physics Procedia 31, p. 35. <http://www.sciencedirect.com/science/article/pii/S1875389212011923>.
- Ruskov, I., Kopatch, Yu.N., Skoy V.R., Dermendjiev E., Hamsch F.-J., Shvetsov V. N., Sedyshev P.V., Pantelev Ts., L. B. Pikelner L.B., Janeva N., Negovellov S. I., Mareev, Yu. D., Mezentseva Zh.V., Ivanov I., 2013. Experimental Setup for Investigation of the Resonance Neutron Induced Fission of ^{239}Pu , THEORY-2 Scientific Workshop on Nuclear Fission Dynamics and the Emission of Prompt Neutrons and Gamma Rays". 28-30 November 2012, Biarritz, France. Physics Procedia 47, p.137. <http://www.sciencedirect.com/science/article/pii/S1875389213004495>.
- Skoy, V.R., Kopatch Yu.N., Ruskov I., 2014. A versatile multi-detector gamma-ray spectrometry system for investigation of neutron induced reactions. 21st International Seminar on Interaction of Neutrons with Nuclei, ISINN-21, 20–25 May 2013, Alushta, Ukraine, pp. 242-248. <http://isinn.jinr.ru/proceedings/isinn-21/pdf/ruskov.pdf>.
- Valkovic, V., Sudac, D., Obhodas, J., Eleon, C., Perot, B., Carasco, C., Sannié, G., Boudergui, K., Kondrasovs, V., Corre, G., Normand, S., Woo, R., Bourbotte, J.M., 2013. The use of alpha particle tagged neutrons for the inspection of objects on the sea floor for the presence of explosives. Nucl. Inst. Meth. A 703, pp. 133-137, <http://www.sciencedirect.com/science/article/pii/S016890021201443X#>.
- VNIIA, 2014. Neutron Generators for Analysis of Substances and Materials. ING-27 gas-filled neutron tube based neutron generator. <http://www.vniia.ru/eng/ng/element.html>, http://www.vniia.ru/eng/ng/docs/ing_element_eng.pdf.