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Accelerator Based Neutron Source VITA for Measuring Nuclear Reaction Cross Sections and for Irradiating Advanced Materials

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A compact accelerator-based neutron source has been proposed and created at the Budker Institute of Nuclear Physics in Novosibirsk, Russia. An original vacuum insulated tandem accelerator (VITA) is used to provide a dc proton/deuteron beam. The ion beam energy can be varied within a range of 0.3–2.3 MeV, keeping a high-energy stability of 0.1 %. The beam current can also be varied in a wide range (from 1 nA to 10 mA) with high current stability (0.4 %). VITA is used to generate a neutron flux via the ^{7}Li(p,n)^{7}Be or ^{7}Li(d,n) reactions, α-particles through ^{7}Li(p,α)α and ^{11}B(p,α)$\alpha\alpha$ reactions, 478 keV photons through ^{7}Li(p,p′γ)^{7}Li reaction, and positrons through ^{19}F(p,αe^{+}e^{-})^{16}O reaction. The facility provides a neutron beam of almost any energy range: cold, thermal, epithermal, monoenergetic, and fast. The facility is used to study radiation blistering of metals during ion implantation, for the development of boron neutron capture therapy including use in clinics, for radiation testing of steel and boron carbide for ITER and fibers for CERN, for studying the composition of films by back-scattered protons, for in-depth investigation of the ^{11}B(p,α)$\alpha\alpha$ neutronless fusion reaction, for measuring nuclear reaction cross sections, *etc*. The report will describe the VITA, present and discuss the results obtained, and declare plans.

1. Introduction

The compact neutron source has been proposed and developed at the Budker Institute of Nuclear Physics and enables the generation of a stable neutron beam [1]. Neutrons are produced by the following reactions: ^{7}Li(p,n)^{7}Be or ^{7}Li(d,n). With different moderators, the neutron energy can vary in over a wide range of energies. The neutron source has applications in various fields, such as: boron neutron capture therapy, activation studies of materials, blistering studies of materials, fundamental studies issues of physics, and other applications.

2. Materials and Methods

Accelerator based neutron source VITA and a lithium target has been proposed and developed at the Budker Institute of Nuclear Physics in Novosibirsk, Russia [1]. The VITA is used to provide dc proton/deuteron beam with energy within a range of 0.3–2.3 MeV with current from 1 nA to 10 mA. The layout of the facility is shown in Figure 1.

The accelerator based neutron source VITA consists of vacuum-insulated tandem accelerator for obtaining a high-power DC proton beam, lithium target for generating neutrons and set of beam shaping assemblies. The lithium target is placed in the five possible positions.

The neutron source generates a stable monoenergetic proton or deuteron beam. Using different moderators the neutron energy can vary over a wide range of energies: cold (D_2O at cryogenic temperature), thermal (D_2O or plexiglass), epithermal (MgF_2 moderator), exclusively epithermal, over-epithermal, monoenergetic, fast. The facility is the source of two bright photon lines (478 keV, 511 keV), α-particles and positrons.

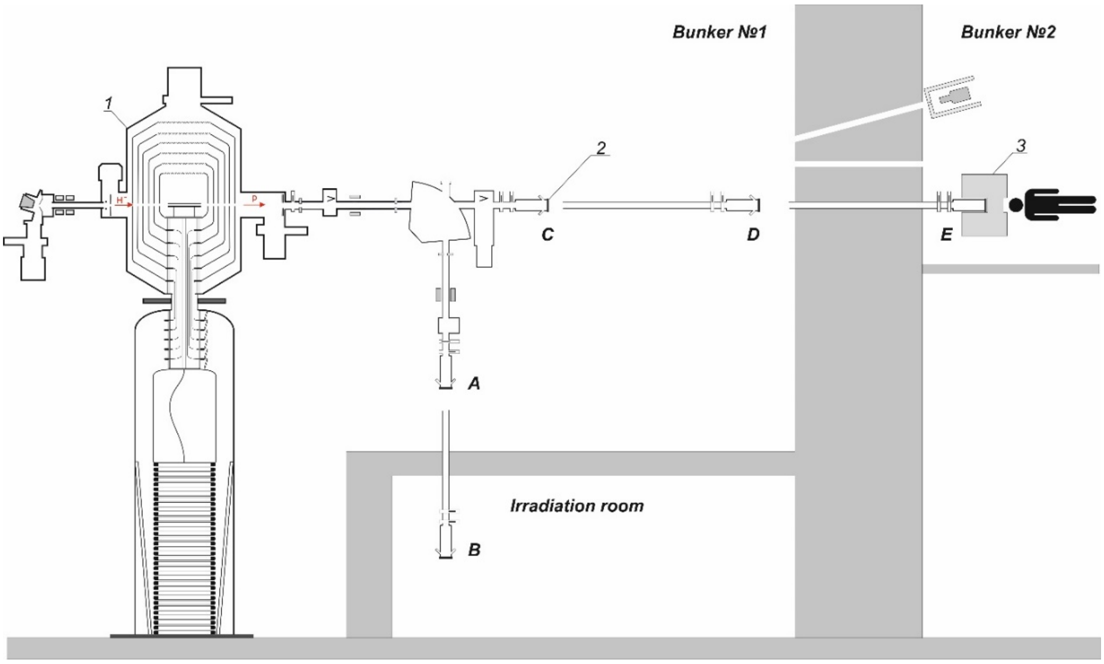

Figure 1. Layout of the experimental facility: 1 – vacuum-insulated tandem accelerator, 2 – lithium target, 3 – beam-shaping assembly. A, B, C, D, E – lithium target placement positions.

3. Study of metals radiation blistering during ion implantation

Using a CCD camera and a remote microscope, the in-situ observation dynamics of blister formation on copper and tantalum surfaces were carried out [2, 3].

It was found that the threshold of blister formation on copper surface depends on copper purity, in the purer copper it is greater. The maximum value of the threshold is $3\ 10^{19}$ cm^{-2}, the minimum one is 7 times less. The size of blisters on the copper surface depends on the purity copper, in cleaner copper the blisters are larger. The blister size varies from 40 ± 20 to 160 ± 50 μm. It has been found that after the blisters appear on the copper surface, further irradiation does not lead to surface modification.

Tantalum was found to be much more resistant to blister formation than copper. The threshold of blister formation in the form of bubbles or flakes on the tantalum surface exceeds $6.7\ 10^{20}$ cm^{-2}. At a fluence of $3.6\ 10^{20}$ cm^{-2} the surface modificates in the form of relief with a characteristic cell size of 1 μm.

An example image of the resulting blisters is shown in Figure 2. The blister was cut off with an electron beam to see its inner structure.

Figure 2. Electron microscope images of the blister of coarse-grained copper.

4. Development of the boron neutron capture therapy

Historically, VITA was proposed and created for the development of the boron neutron capture therapy (BNCT). Since 2008 year, when first neutrons were detected, there were made lots of investigations, dedicated to BNCT: trials on the different cell cultures, on laboratory mice and, nowadays, treatment of pets with natural tumors [4-16]. Photos of the trials are shown in Figure 3.

Figure 3. Photos of the BNCT trials on VITA. Upper left – Boron delivery drugs for BNCT, upper right – mice with an artificially injected tumor under the neutron generating target, bottom left – pet "Prometeus", bottom right – pet "Cappa".

The accelerator based neutron source VITA was installed in Xiamen, China. Nowadays preclinical human trials are conducted there [17]. Photo of the VITA for Xiamen (China) is shown in Figure 4.

Since the BNCT trials on the cell cultures, mice and animals were successful the Russian government resolution in 2021 year was to create an accelerated neutron source VITA for the Blokhin Oncology Research Center (Moscow, Russia). Nowadays it located in the BINP and in the stage of installing, by the end of 2024 it is planned to launch VITA at the Blokhin Oncology Research Center.

Figure 4. Accelerator based neutron source VITA in Xiamen, China.

5. Radiation testing of materials

VITA is actively used for radiation testing of perspective materials for ITER, CERN and other large facilities [18].

For ITER VITA has provided neutron activations study of sintered boron carbide ceramics (Viral). In the Figure 5 it can be seen the measured by the HPGe detector spectrum of γ-rays emitted by Viral after fast neutron irradiation.

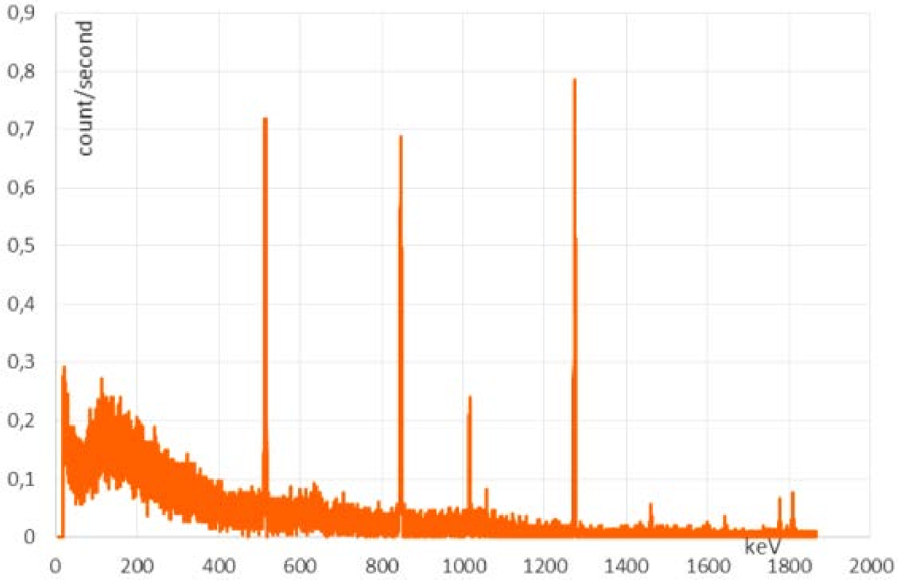

Figure 5. Measured spectrum of γ-rays emitted by sintered boron carbide ceramics (Virial) after fast neutron irradiation. On the vertical axis: the number of detector counts; on the horizontal axis: photon energy in keV.

For CERN on VITA was made a month experiment, in which fiber optics for experiments on the LHC in high-luminosity mode has been irradiated by fast neutrons, generated during ^{7}Li(d,n)^{8}Be reaction. Samples were irradiated to a fluence of $3{\cdot}10^{14}$ fast neutrons/cm^2 with real-time measurements of fiber optics transparency factor. After this experiment it was established that VITA can easily provide day-by-day generation of fast/epithermal neutrons up to 8-10 hours per day. In the Figure 6 is shown the dependence of optical fibers transparency versus fast neutron fluence up to a value of $3{\cdot}10^{14}$ neutrons/cm^2. There is a quite degradation of fiber optics, when neutrons are generating, without neutron generation optics is recovering, but not to the 100 %.

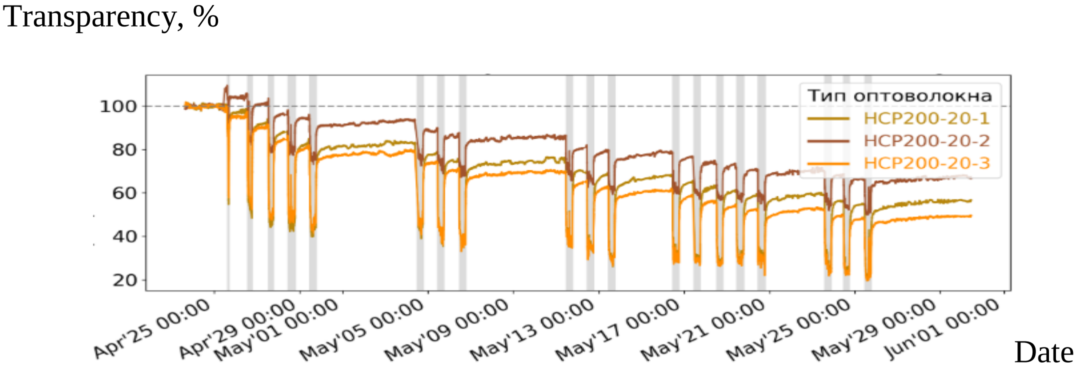

Figure.6. Dependence of optical fiber transparency versus fast neutron fluence.

Simultaneously with the fiber optics irradiation at VITA also irradiated:

– Semiconductor photomultiplier tubes and dc-dc converters for the ATLAS detector of the CERN Large Hadron Collider (Geneva, Switzerland);

– A diamond detector for the International Thermonuclear Experimental Reactor (ITER, Cadarache, France);

– Boron carbide plates for ITER;

– Neodymium magnets for the hybrid quadrupole lens of the high-power linac at the Institute of Theoretical and Experimental Physics (Moscow, Russia);

– Natural and synthetic diamonds for the Nikolaev Institute of Inorganic Chemistry (Novosibirsk, Russia) [19];

– Gas sensors based on titanium phthalocyanines for Novosibirsk State University (Russia).

6. Studying the composition of films by back-scattered protons

On VITA proton beam, collimated by a diaphragm, is actively used for studying of the different targets compositions, investigated by energy analysis of backscattered protons. The spectrum of backscattered protons measured with a semiconductor silicon detector (Si Charged Particle Radiation Detectors for Alpha Spectroscopy). Using obtained spectrum and simulations in the SIMNRA v.7.03 (Max Planck Institute for Plasma Physics, Germany) the depth distribution of elements on the sample is determined.

Example of this back-scattered protons analysis is provided in the Figure 7. The thickness of the main lithium layer is 30 μm, of the lithium oxide is 37 nm, of the carbon is 0.9 nm. The possibility to detect different elements defined by the element concentration, exposure time and cross-section of the interactions. Therefore, the 0.9 nm of carbon can be detected, due to resonance elastic scattering of the proton on the carbon.

The important conclusion that lithium target, produced in Budker INP, is covered by the thin films of lithium oxide and carbon, they perform a protective function, and these knowledge will be used in the delivery of lithium targets to the consumer.

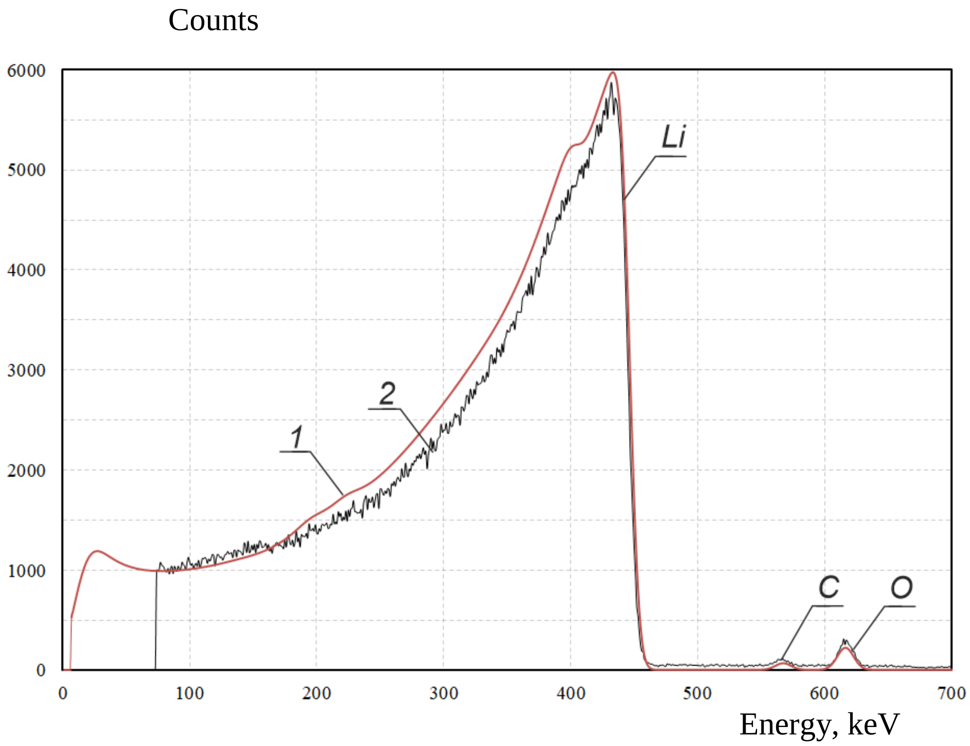

Figure 7. Spectrum of the back-scattered from the lithium target protons. 1 – SIMNRA simulation, 2 – experimental data, Li, C, O – lithium, carbon and oxygen peaks.

7. Measurements of the nuclear reaction cross sections

On VITA were measured cross-sections of the ^{7}Li(p,p′γ)^{7}Li, ^{7}Li(p,α)α reactions, experimental results were included in the international databases (IBANDL, EXFOR) [20-22]. Measured spectrum are shown in Figures 8 and 9.

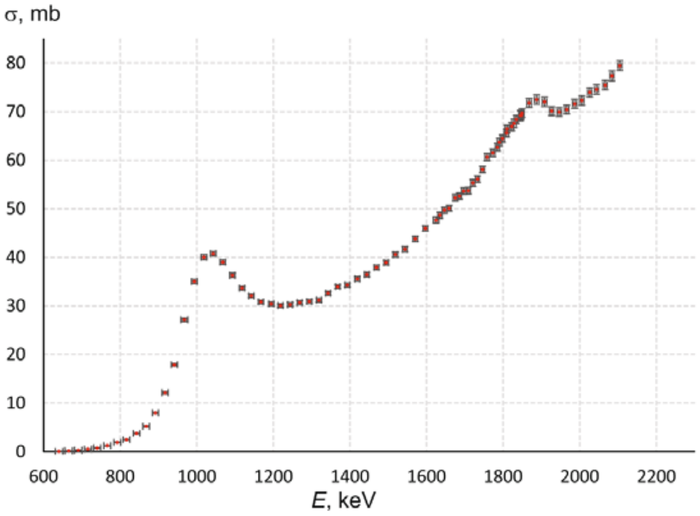

Figure 8. Cross-section of the ^{7}Li(p,p′γ)^{7}Li reaction in a range from 0.6 MeV to 2.15 MeV.

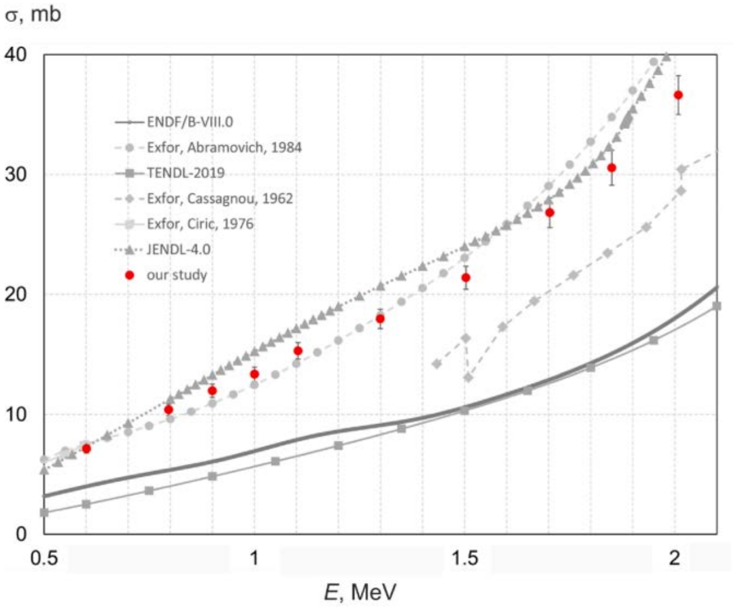

Figure 9. ^{7}*Li(p,α)*^{4}*He reaction cross section.*

From the Figure 9 it can be seen, that our data are similar to the JENDL data and 2 times higher, than data from ENDF/B and TENDL.

Nowadays the data for ^{11}B(p,α)αα, ^{6}Li(d,) and ^{7}Li(d,) are obtained and processing. Detailed information is presented in the paper [23].

8. Conclusion

High flux neutron source based on a vacuum-insulated tandem accelerator (VITA) and a lithium target has been proposed and developed at the Budker Institute of Nuclear Physics in Novosibirsk, Russia. The compact neutron source enables the generation a stable neutron beam, two bright photon lines (478 keV, 511 keV), α-particles and positrons. In this paper the main studies conducted at VITA were summarized.

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