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VITA high flux neutron source for various applications

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Abstract. A 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. We describe VITA which provides a dc proton/deuteron beam with an energy within a range of 0.6–2.3 MeV with a current from 1 nA to 10 mA. VITA is also capable of producing α-particles through the ^{7}Li(p,α)α and ^{11}B(p,α)$\alpha\alpha$ reactions, 478 keV photons through the ^{7}Li(p,p$'\gamma$)^{7}Li reaction and positrons through the ^{19}F(p,e^{+}e^{-})^{16}O reaction. We present several applications of this source: boron neutron capture therapy, nuclear cross sections determination, lithium target study, radiation blistering of metals during proton implantation and the radiation testing of promising materials.

Keywords: Neutron source, vacuum-insulated tandem accelerator, lithium target

1. The VITA high flux neutron source

The compact neutron source which has been proposed and developed at the Budker Institute of Nuclear Physics (BINP) enables a stable neutron generation at the target in Novosibirsk, Russia [3,11]. The high flux neutron source is based on a vacuum-insulated tandem accelerator (VITA) and a lithium target.

Neutrons are produced by the following reactions: ^{7}Li(p,n)^{7}Be or ^{7}Li(d,n). Thanks to the use of different moderators, the neutron spectra cover a wide range of energies. The neutron source has applications in various fields: boron neutron capture therapy, activation studies of materials, blistering studies of materials, fundamental physics studies and other miscellaneous applications. VITA is used to provide dc proton/deuteron beam with an energy within a range of 0.6–2.3 MeV with current from 1 nA to 10 mA. The layout of the facility is shown in Fig. 1.

The accelerator consists of a source of negative hydrogen ions and a vacuum insulated tandem accelerator which accelerates H^-. Two electrons are lost inside the stripping argon target. After that, protons are accelerated by the same potential. They pass through a bending magnet and a scanning system in the vertical path or continue to move in the horizontal path and the beam hits a lithium target where a nuclear reaction ^{7}Li(p,n)^{7}Be or ^{7}Li(d,n) takes place. The target is a copper disk with a thin layer of crystalline lithium (thermally evaporated on the copper disk). The lithium target is placed in five possible positions.

The neutron source can generate a stable monoenergetic proton or deuteron beam as well as a monoenergetic neutron beam. Using different moderators (magnesium fluoride, plexiglass or heavy water), the neutron energy

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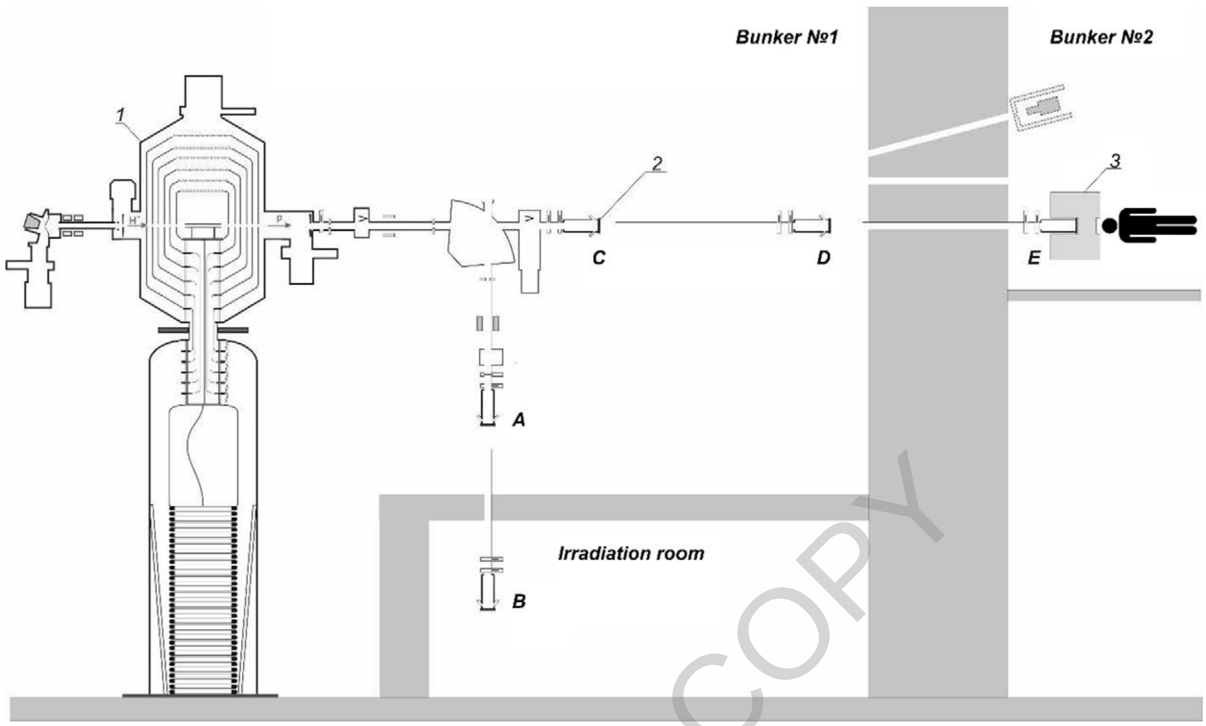

Fig. 1. Layout of the experimental facility: 1 – vacuum-insulated tandem accelerator, 2 – lithium target, 3 – beam-shaping assembly. A, B, C, D, E – lithium target placement positions.

can vary over a wide range of energies: cold, thermal, epithermal, exclusively epithermal, over-epithermal, monoenergetic and fast. This facility is the source of two bright photon lines (478 keV, 511 keV), α-particles and positrons.

2. Applications

The neutron source is currently undergoing a lot of research on projects in various directions. This article gives a brief overview of the main ones and a more detailed description of the latest research.

2.1. Boron neutron capture therapy

Originally, the accelerator-based neutron source of the BINP was created for boron neutron capture therapy. The neutron source was a prototype of the commercial neutron beam system for hospital-based BNCT manufactured by TAE Life Sciences (Foothill Ranch, CA, USA). TAE Life Sciences installed its first commercial neutron beam system at the new BNCT Center at Xiamen Humanity Hospital in Xiamen, P.R. China in 2020 [1]. A similar accelerator will be built for the National Oncological Hadron Therapy Center (CNAO) in Pavia, Italy and for the National Medical Research Center of Oncology in Moscow, Russia.

The therapy itself consists in introducing a boron-containing drug into the tumor cells followed by irradiation with a beam of epithermal neutrons. Thermal neutrons interact with boron and the reaction $^{10}B(n,\alpha)^{7}Li$ produces a lithium nucleus and an α-particle with an energy release of 2.79 MeV within 10 μm, which corresponds to cell sizes in mammals.

For quality therapy, there are several key factors to be aware of, one of which is the dose the patient receives when he or she is exposed to radiation. In BNCT, the total absorbed dose is the sum of four dose components with different RBE [6,7,9,10,17,18]: boron dose, high-LET dose from the $^{14}N(n,p)^{14}C$ reaction ("nitrogen" dose), fast neutron dose and γ-ray dose. Methods for measuring all kinds of absorbed dose components have been developed at the facility.

Today, the most pressing issue in BNCT is the development of a new boron-containing drug that will selectively accumulates in cancer cells. Our team collaborates with biologists and chemists in radiobiological research on mice and cell cultures. Nowadays, cats and dogs which have spontaneous tumors are treated with the neutron source [8].

2.2. *Study of nuclear reaction cross sections*

The accelerating neutron source is also widely used to measure the cross sections of interactions of protons with matter, for example in the reaction $^7Li(p,p'\gamma)^7Li$. This reaction cross section with photon yield from a thick lithium target at proton energies from 0.625 to 2.25 MeV have been measured with a high purity germanium detector. The spectrometer absolute and relative sensitivities was calibrated with reference radionuclide sources of photon radiation. The measurement results have been compared with those presented in the EXFOR nuclear reaction database and with other data published in open sources [16]. Lately, the cross section of $^7Li(p,\alpha)\alpha$ reaction was measured [15].

2.3. *Lithium target analysis*

Here, we focus in more detail on the study of some parameters of a lithium neutron-generating target designed specifically for research in the BNCT field – measuring the neutron yield and determining the elemental composition of the target. This tasks well illustrates the possibilities of very accurate determination of thin film thicknesses (down to 1-2 nm), as well as their influence on such processes as neutron yield from a neutron-generating target.

Let us start with measurements of the neutron yield from a lithium target. Since the products of the $^7Li(p,n)^7Be$ reaction are not only neutrons but also beryllium-7 radioactive atomic nuclei, measuring the amount of ^7Be nuclei allows to unambiguously determine the flux of generated neutrons. The radioactive atomic nucleus ^7Be transforms back into lithium-7 as a result of electron capture with a half-life of 53.22 days. In 10.3 % of cases, the decay was accompanied by the emission of a 478 keV photon. If we do not allow beryllium to evaporate from the lithium target, the measurement of the activation of the target allows us to determine the number of ^7Be nuclei produced which is equal to the number of neutrons generated. No previous measurements of the neutron yield from a real lithium neutron-generating target have been made. Our measurements coincide well with the theoretical calculations [4].

In the same experiment, to determine the composition of the lithium target, we used the method of energy analysis of backscattered protons. A series of experiments were carried out depending on the proton beam fluence and power density. The experiment consisted of irradiating the target with a proton beam with gradually increasing proton beam power density followed by the measurement of the elemental composition of the target from the energy analysis of the backscattered protons. The obtained spectra of backscattered protons were compared with the spectra simulated using the SIMNRA v.7.03 (Max Planck Institute for Plasma Physics, Germany) [2]. During the measurements, the $\sim$1 cm diameter proton beam was cut by a cooled collimator with a diameter of 1 mm. Protons were scattered on a lithium target and hit the alpha detector located at an angle of 168° to the beam axis. The aperture was lifted when the fluence was gained, and the alpha detector was cut off from the setup with a slide, avoiding its loading. The thickness of the lithium layer was of $\sim$30 μm.

The obtained spectrum of backscattered protons and its modeling (Fig. 2) allowed us to assume that the target consists of the following components: a carbon layer on the target surface, a lithium oxide layer, and a lithium layer on copper substrate. Based on the simulation, a general dependence of the percentage of oxygen in the target was determined (Fig. 3). The thickness of the carbon layer on the surface of the target was also determined and saturates (Fig. 4).

Initially, when pure lithium was sputtered, the lithium oxide layer was $\sim$10 nm thick and the carbon film $\sim$0.5 nm thick. After prolonged irradiation, the oxygen concentration in the target increased by a factor of 5 and the carbon concentration by a factor of 4, which did not affect the neutron yield from the lithium target.

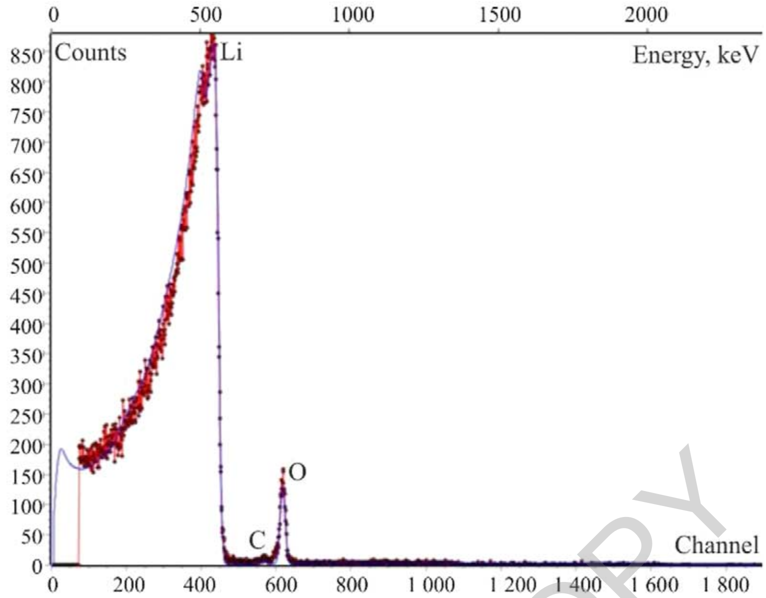

Fig. 2. Spectrum of backscattered protons from a new lithium target, experimental data (red), SIMNRA simulations (blue).

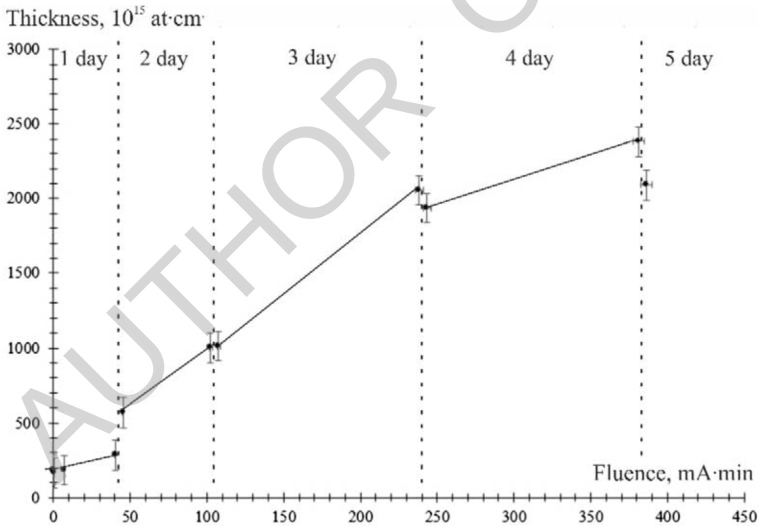

Fig. 3. Dependence of oxygen concentration versus fluence.

Next, the beam power was increased to $\sim$1 kW/cm^2 and the lithium melted. Visual observation of the target with a video camera showed that the lithium surface remained solid, probably thanks to the protective effect of the oxygen layer. At 240°C, the presence of copper (substrate) was visible in the spectrum of backscattered protons (Fig. 5). This was due to the fact that flakes detached from the copper and penetrated the molten lithium.

This work is critical to ensure a stable neutron flux generation for boron neutron capture therapy and other applications over long periods of time, including when dealing with critically high temperatures of the target surface.

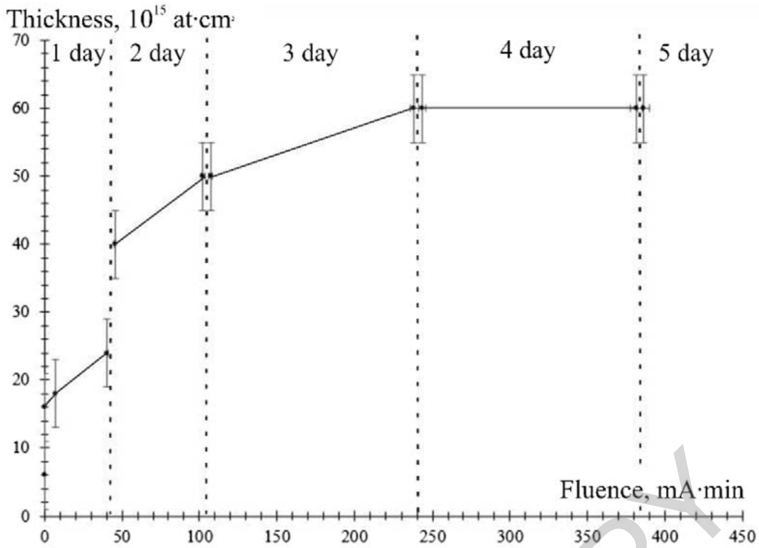

Fig. 4. Dependence of the carbon layer thickness versus fluence.

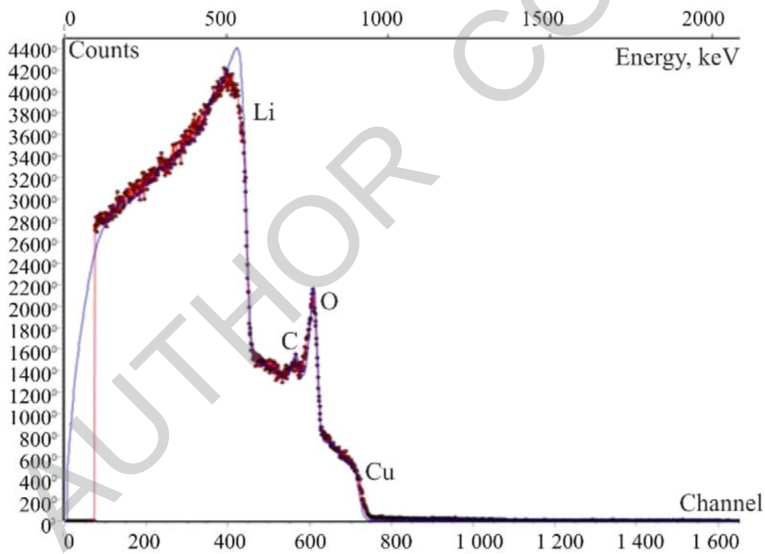

Fig. 5. Spectrum of backscattered protons from a melting lithium target, experimental data (red), SIMNRA simulations (blue).

2.4. Radiation blistering of metals during proton implantation

One of the significant problems of working with powerful beams is radiation damage. There are several types of damage, one of them being blistering. By the term blistering, we mean the deformation of the surface layer of the irradiated metal caused by the accumulation of gas atoms at the stagnation depth, implanted during ion irradiation. Blistering manifests itself in the form of dome-shaped elevations (bubbles) on the metal surface and exfoliates itself off thin surface layer. The accelerated neutron source was applied to study blistering on a lithium target that was specifically designed for BNCT. A thin layer of material showed strong resistance to radiation blistering and results are described in [5].

2.5. Radiation testing of promising materials

Another common application of a neutron source is to test equipment or materials for radiation resistance when exposed to a neutron beam of different energies. The neutron source was used to measure the content of hazardous impurities in boron carbide samples caused by irradiation of fast neutrons. The boron carbide samples were specially developed for the thermonuclear fusion reactor ITER [12–14].

Recently, we have used the neutron source for monthly radiation tests of fibers of the laser calorimeter calibration system of the Compact Muon Solenoid electromagnetic detector developed for the High-Luminosity Large Hadron Collider in CERN.

3. Conclusion

The 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. This compact neutron source enables the generation of a stable neutron beam, two bright photon lines (478 keV, 511 keV), α-particles and positrons. We have shown that this source allows to perform studies of many types: BNCT, nuclear cross section determination, lithium target characterization and temperature dependence, blistering of metals during proton implantation and radiation testing.

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