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NUCLEAR EXPERIMENTAL TECHNIQUE

A Fast-Neutron Source Based on a Vacuum-Insulated Tandem Accelerator and a Lithium Target

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Abstract—The production of a deuteron beam in a vacuum-insulated tandem accelerator and the generation of fast neutrons from a lithium target have been investigated. The possibility of using a source of fast neutrons for radiation testing of materials and for fast-neutron therapy is discussed.

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An accelerator source of epithermal neutrons is functioning at the Budker Institute of Nuclear Physics (BINP) [1, 2]. This source has been created for the development of a prospective method for treating malignant tumors, i.e., boron neutron capture therapy [3, 4]. The source consists of a vacuum-insulated tandem accelerator, which produces a proton beam, and a lithium target in which neutrons are generated in the ^{7}Li(p, n)^{7}Be threshold reaction. An epithermal-neutron beam suitable for boron neutron capture therapy was obtained and successful biological studies were carried out with the source [5, 6]. The developed neutron source acts as the prototype of the facility, which will soon be put into operation in China for the treatment of patients with boron neutron capture therapy.

Using this neutron source, a method for the rapid detection of explosives and narcotic substances was also developed [7], and the concentration of hazardous impurities in boron carbide samples produced for the International Thermonuclear Experimental Reactor was measured [8]. In addition, it is expected that the source will be used for radiation tests of fibers of the laser calorimeter calibration system designed to modernize the CMS electromagnetic detector Phase II to work on the High-Luminosity Large Hadron Collider at CERN [9].

The aim of this study was to obtain a deuteron beam on a vacuum-insulated tandem accelerator and to generate fast neutrons in a lithium target, which are acceptable for radiation testing of optical fibers, fast-neutron therapy, and for other applications.

THE EXPERIMENTAL SETUP

The study was conducted on an accelerator-based source of epithermal neutrons at the BINP [2]. The diagram of the experimental setup is shown in Fig. 1. The proton beam with an energy of 2 MeV and a current as high as 9 mA is produced as follows. A beam of negative hydrogen ions with an energy of 20 keV is pulled from the surface-plasma source *1*. The beam is bent through an angle of 15° in the magnetic field of the ion source and then is focused by the magnetic lens *2* on the accelerator input *3* and accelerated in it to an energy of 1 MeV. Negative hydrogen ions are converted into protons in a gas stripper inside the high-voltage electrode of the accelerator and protons are accelerated by the same potential of 1 MV to an energy of 2 MeV. Next, the proton beam is transported to the lithium target *13*, which is usually placed in the vertical part of the beam transport line behind the gate valve *16*. In this experiment, the target is placed in the horizontal part behind the gate valve *11*.

The target is a copper disk with a diameter of 144 mm and a thickness of 8 mm. A thin layer of crystalline-density lithium was thermally sprayed in the form of a 82-mm-diameter circle onto the copper disk from the side facing the proton beam. On the reverse side of the copper disk there are four two-way spiral channels for water cooling [10]. A flat aluminum disk with one hole at the center for supplying cooling water and two holes on the periphery for water drainage is pressed to the back of the copper disk. At a characteristic water flow rate of 15–17 L/min, a turbulent water flow at a speed of 3.5–4.0 m/s is realized in the cooling channels, which provides efficient heat removal [11].

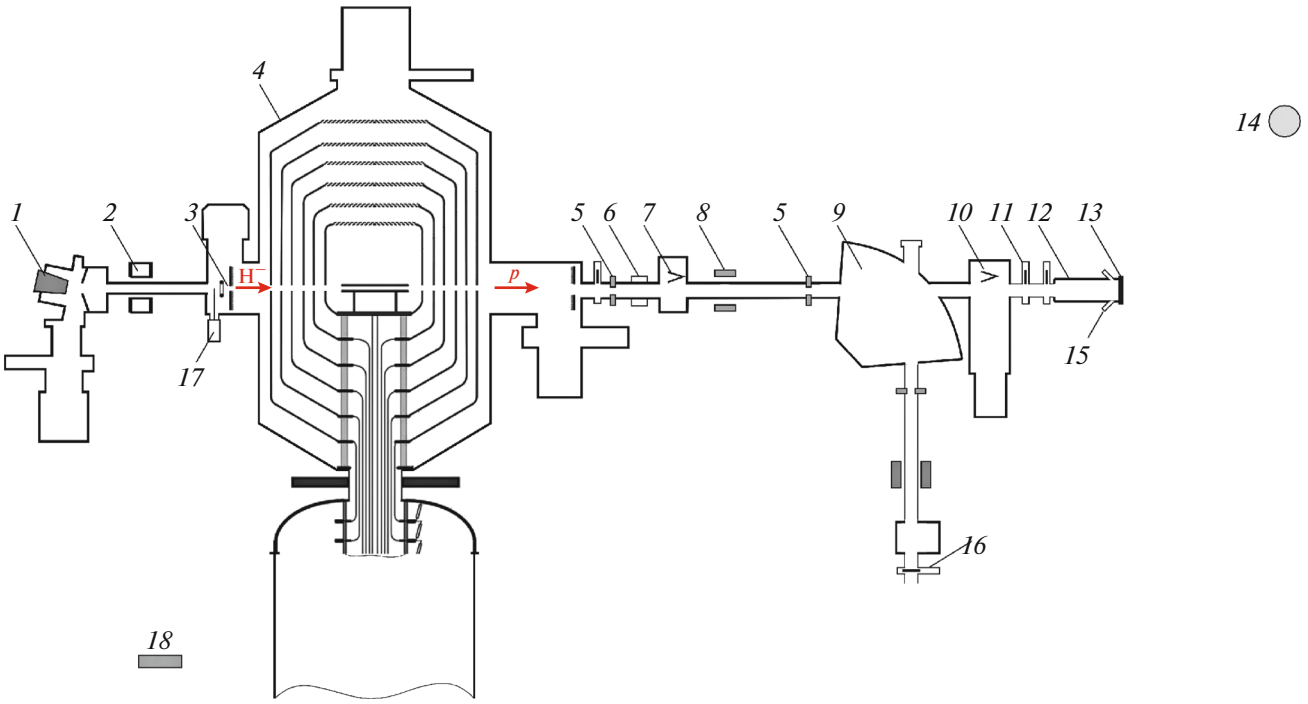

Fig. 1. The experimental setup: (*1*) source of negative hydrogen ions, (*2*) magnetic lens, (*3*) input cooled diaphragm of the accelerator, (*4*) vacuum-insulated tandem accelerator, (*5*) cooled diaphragm with an aperture of 26 mm, (*6*) nondestructive DC current transformer, (*7*) sliding Faraday cup in the diagnostic chamber at the exit from the accelerator, (*8*) corrector, (*9*) bending magnet, (*10*) sliding Faraday cup in the diagnostic chamber behind the bending magnet, (*11*, *16*) gate valves, (*12*) vacuum chamber, (*13*) lithium target, (*14*) neutron dosimeter, (*15*) pipes with windows for observation, (*17*) wire scanner, and (*18*) neutron detector.

Lithium is deposited on a sample at a special facility according to a scenario similar to the procedure described in [12]. After lithium deposition, the sample, together with the part of the vacuum chamber *12* that is closed by the gate valve to maintain a vacuum inside, is disconnected from the lithium-deposition facility, transferred to the experimental setup, and connected to the proton-beam transport line.

The transverse dimension of the proton beam at the exit from the accelerator *4* is approximately 1 cm [13]. The proton current is measured and monitored by an NPCT non-destructive DC current transformer *6* (Bergoz Instrumentation, France), the position of the beam is monitored by thermocouples inserted into the cooled diaphragms *5*, and the beam position and current are measured by sliding Faraday cups in the diagnostic chambers *7* and *10*. The position and size of the proton beam on the surface of the lithium target *13* is measured and monitored by eight thermocouples inserted into the holes drilled in the copper disk of the target from its side surface. The in-situ state of the target surface is monitored by a Hikvision camera through one of the nozzles *15* with fused silica glass.

The ambient dose equivalent rate of neutron radiation is measured by a BDMN-100-07 detection unit (Doza Scientific and Production Company, Zelenograd, Moscow, Russia) [14], which consists of a spherical moderator with a UDMN-100 detection unit enclosed in it. The detection unit *14* is fixed in place on the wall of the radiation-protected room at a distance of 3.6 m from the target at an angle of 34° with the proton beam. The error in measuring the dose rate is 25%; it is not taken into account in the data presented below.

The neutron flux is controlled by the neutron detector *18* with a lithium-containing GS20 scintillator (Saint Gobain Crystals, United States) coupled to a Hamamatsu R6095 photomultiplier tube with an MHV12-1.5K1300P high-voltage power supply (TRACO Electronics, Japan). The detector is placed at a distance of 7.3 m from the target at an angle of 146° with the proton beam.

RESULTS OF THE MEASUREMENTS AND DISCUSSION

A neutron beam of the epithermal energy range with a minimum quantity of fast and thermal neutrons is required for boron neutron capture therapy of malignant tumors. The best reaction for obtaining such a neutron beam is the ^{7}Li(p, n)^{7}Be threshold reaction, since the yield is maximal and the neutron energy is minimal, i.e., below 1 MeV [15, 16]. Radiation resistance tests, on the contrary, require neutrons

with an energy of more than 1 MeV, which are obtained in exothermic reactions:

$$d + d \rightarrow {}^{3}\mathrm{He} + n + 3.265\ \mathrm{MeV},$$

$$\mathrm{T} + d \rightarrow {}^{4}\mathrm{He} + n + 17.588\ \mathrm{MeV},$$

$${}^{7}\mathrm{Li} + d \rightarrow {}^{8}\mathrm{Be} + n + 15.028\ \mathrm{MeV},$$

$${}^{7}\mathrm{Li} + d \rightarrow 2{}^{4}\mathrm{He} + n + 15.122\ \mathrm{MeV},$$

$${}^{9}\mathrm{Be} + d \rightarrow {}^{10}\mathrm{B} + n + 4.362\ \mathrm{MeV}.$$

The calculated neutron yield in these and a number of other reactions in thick targets was presented in [4, 17]. The Li(d, n) reaction is characterized by the highest neutron yield at a deuteron energy of more than 0.8 MeV. Thus, at an ion energy of 2 MeV the neutron yield in the Li(d, n) reaction is 13.5×10^{11} mC^{-1}, while the neutron yield in the Be(d, n) and Li(p, n) reactions are 6×10^{11} and 1.1×10^{11} mC^{-1}, respectively [15].

There are two channels of the Li(d, n) reaction: ^{7}Li(d, n)^{8}Be and ^{7}Li(d, n)2^{4}He. In the first case, when two particles are reaction products, the neutron energy is equal to 13.36 MeV if the deuteron energy is ignored, and is higher if the deuteron energy is taken into account. In the second case, when three particles are produced the neutron spectrum is not monochromatic but is wider, with lower energy. The neutron spectrum of the Li(d, n) reaction was measured at a deuteron energy of 2.9 MeV in [18]. It contains two components: the first with an average energy of 13 MeV, which is associated with the first channel of neutron generation, and the second with an average energy of 3 MeV, which is due to the second channel. The average neutron energy is 5.68 MeV. At a deuteron energy of 2 MeV, the spectrum of generated neutrons will not differ much, since the energy yield in the reaction is substantially higher than the deuteron energy.

For a powerful fast-neutron flux to be generated in the Li(d, n) reaction, we proposed to use a vacuum-insulated high-current tandem accelerator, which initially did not allow us to obtain a deuteron beam, and to use a scenario with the injection of a deuterium negative-ion beam with an energy that was one-half of the energy of the injected hydrogen ions.

The deuteron beam was produced in the accelerator as follows. Hydrogen was replaced with deuterium in the surface-plasma source *1*, and a stable discharge was obtained. Since deuterium is two times heavier than hydrogen, a beam of negative deuterium ions with an energy of 10 keV was pulled from the source. This energy was two times less than the usual energy when working with hydrogen, so that the ion beam was bent through the same angle in the self-magnetic field of the source and was directed along the accelerator axis. The beam of negative deuterium ions was then focused by the magnetic lens *2* at the entrance to the accelerator *3*, controlling the beam position and size with an OWS-30 oscillating wire scanner (D-Pace, Canada) *17* [19]. The focal length of a magnetic lens is proportional to the mass of the ions of the focused beam, but the lower energy of the deuterium ions makes it possible to focus the ion beam at the accelerator input by almost the same current of the lens coils. A higher current delivered to the lens was required to compensate for the greater effect of the space charge on the trajectory of deuterium ions due to their lower velocity (the discovered effect of the space charge on the focusing of a hydrogen ion beam was described in [19]).

The characteristics of the ion-optical system of the accelerator are determined by the electrostatic lenses of the diaphragms and, to the greatest extent, by the input diaphragm, whose focal lengths are independent of the ion mass. At the same time, the focusing point of the injected ions and their velocity determine the further ion trajectories. Together with the uncertainty of the degree of compensation for the space charge, based on the calculations, all these issues did not allow us to reliably state that it was possible to obtain a deuteron beam in the accelerator without damaging it, in particular, without burning uncooled diaphragms of the accelerating electrodes. For this reason, the main efforts were concentrated on focusing deuterium ions at the accelerator input at a place that was previously determined to be optimal for obtaining a proton beam. After the beam was aligned and focused at the input of the accelerator under control of the wire scanner, the voltage was applied to the accelerator and a deuteron beam with an energy of 2 MeV and a current of 1.1 mA was produced at its output. The position and size of the ion beam were monitored using Hikvision cameras that were aimed at the input and output diaphragms of the accelerating electrode and detected visible light generated by the ionization of the residual and stripping gas with ions [20]. The passage of the ion beam was optimized by a magnetic lens *2* and a corrector *8* so that minimal and symmetrical heating of the cooled diaphragms 5 was achieved in the deuteron-beam transport line.

First, the deuteron beam was directed to the Faraday cup *7* that was located near the exit from the accelerator. The Faraday cup was a cooled copper cone with nine thermocouples for monitoring the position of the ion beam; it was equipped with motion entry. The detector *18* and dosimeter *14* detected the generation of neutrons. The Faraday cup *7* was then removed from the axis, and the beam was redirected to the identical Faraday cup *10* that was placed behind the bending magnet *9* (the magnet was turned off). The detector and dosimeter also detected generation of neutrons. The neutron dose rate, measured by the dosimeter *14* at a distance of 4.4 m from the Faraday cup, was 9.0 ± 0.3 mSv/h. The deuteron beam was then guided to the lithium target *13*. The dosimeter located 3.6 m from the target went off the scale, but there was indirect evidence that it should have shown the dose rate to be higher by 100 times, at the level of

1 Sv/h. The point is that the dose rate measured by a similar dosimeter on the outer wall of the radiation-protected room increased by 68 ± 8 times; an additional increase by 1.5 times should be provided by a closer location of the dosimeter, i.e., 3.6 m instead of 4.4 m.

The activation of the setup was measured at the end of the neutron generation, and significant activation of the Faraday cups was detected. The spectrum of the induced activity was measured using the SEG-1KP-IFTP γ-ray spectrometer based on a high-purity germanium semiconductor detector, and the time dependence of the count rate in the selected peak was measured. It was established that the emitted γ rays had an energy of 511 keV and the half-life of the produced isotope was 10 min. Such decay parameters fully corresponded to the parameters of the ^{13}N radioactive isotope, which was most likely produced by the $^{12}C(d, n)^{13}N$ reaction due to possible coating of the copper cone surface with a thin film of oil or carbon.

Let us estimate the dose rate of neutrons produced by the interaction of 2-MeV deuterons with lithium nuclei. The evaluated neutron yield in the $^{7}Li(d, n)$ reaction is 1.35×10^{12} s^{-1} at a current of 1 mA [17]. A layer of natural lithium with a 92.5% concentration of the ^{7}Li nuclide was sputtered onto the target. In this case, the neutron yield of natural lithium was 1.4×10^{12} s^{-1} if the current obtained in the experiment was 1.1 mA.

The unit neutron fluence can be converted into the ambient dose equivalent using the recommendations for anteroposterior irradiation given in [21, 22]. The conversion factor is 1 (μSv/h)/(neutrons/(cm^2 s)) for 1-MeV neutrons, 1.8 (μSv/h)/(neutrons/(cm^2 s)) for 10-MeV neutrons, and 1.257 (μSv/h)/(neutrons/(cm^2 s)) for the neutron spectrum from [18]. The latter value will be used below to calculate the dose.

By multiplying the neutron yield of 1.4×10^{12} s^{-1} by the conversion factor of 1.257 (μSv/h)/(neutrons/(cm^2 s)), we obtain the luminosity of the source, which is equal to 1.75×10^{6} (Sv/h) m^2. Assuming that the radiation source is a point source and the emission is isotropic, we obtain a dose rate of 1.4 kSv/h at a distance of 10 cm and 1.07 Sv/h at a distance of 3.6 m that is equal to the target-to-detector distance. The latter value is in good agreement with the dose rate measured by the dosimeters.

An equivalent neutron fluence of up to 10^{14} cm^{-2} must be attained for radiation testing of optical fibers of the laser calorimeter calibration system. The neutron flux is transformed into the equivalent neutron flux using the ionization loss coefficient obtained by the CERN-RD48 collaboration [23]. This coefficient is equal to 1 for 1-MeV neutrons; it ranges from 1 to 2 at an energy above 1 MeV, is approximately 1 at energies from 200 keV to 1 MeV, and is much less than 1 at energies below 200 keV. Assuming that the radiation source is a point source, the radiation is isotropic, and the ionization loss coefficient is equal to unity, we find that the required fluence of 10^{14} cm^{-2} at a distance of 10 cm will be acquired over 1 day of generation, which is quite feasible.

The neutron source may find other application in fast-neutron therapy. The achieved neutron yield of 1.4×10^{12} s^{-1} is equal to the maximum attainable yield of the NG-12I generator, which has been used for the treatment of patients at the Ural Neutron Therapy Center for a long time [24], and can be further increased. As distinct from the NG-12I generator, a tritium target is not used in our source; therefore, the location of the neutron source may not be bound up to a nuclear center with the tritium production infrastructure.

The neutron yield can be increased: first, by 8% due to the deposition of lithium enriched in the ^{7}Li isotope, which is available and second, by increasing the deuteron beam current by almost 5 times, to 5 mA. However, in the latter case, working with such a current requires measures for reducing the neutron radiation dose outside the radiation-protected room and for shielding the equipment inside the room. Third, the fast-neutron flux density on the sample can be increased by placing a reflector made of a material with a high atomic mass number and the neutron flux density on a patient can be increased by placing a collimator that combines the shield and reflector functions.

CONCLUSIONS

It is proposed to obtain a deuteron beam in an accelerator in order to extend possible applications of the epithermal-neutron source at the Budker Institute of Nuclear Physics. As a result of the study using a diverse set of diagnostic techniques, the injection mode of the accelerator beam of negative deuterium ions with an energy of one-half the energy of injected hydrogen ions was achieved and a stationary deuteron beam with an energy of 2 MeV and a current of 1.1 mA was obtained. The generation of fast neutrons was performed by dumping a deuteron beam onto a lithium target. The neutron yield was 1.4×10^{12} s^{-1}. The operating mode with the deuteron beam is attractive for radiation testing of materials, fast neutron therapy, and other applications.

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