Physics for BNCT

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Abstract  The experience from physical field for the BNCT project realized in NRI (Czech Republic) is presented. The physical methods and equipments for the design, construction and operation of facility for medical application are summarized. The comment is concentrated to the following items, especially: Sources for BNCT, calculation methods, measurement methods, phantoms, monitoring of irradiation, 10B content in tissue determination, construction of facility.

1. Introduction
The development and construction of BNCT facility were realized at LVR reactor of NRI Rez. The BNCT group of specialists from different scientific fields (physics, medicine, chemistry, radiobiology, pharmacology) acquired a rich experience in the course of this long time activity [1], [2]. This paper represents an attempt to present some specific results from the field of physics.

2. BNCT SOURCES
Reactors. The nuclear experimental reactors have been the only neutron sources to provide correct energy spectrum and adequate thermal neutron flux from the beginning of BNCT history. This became more evident when the BNCT moved from the use of a thermal neutron beam to the use of a more energetic, epithermal neutron beam. In a nuclear reactor neutrons are generated by the fission reaction occurring in the core, mean energy is 1.98 MeV. It requires suitable modification in order to be enhanced in the epithermal part and depressed in the thermal and fast components. It should be pointed out as all the BNCT clinical trials performed until now relied on nuclear reactor based neutron sources. A short review of them is demonstrated in Tab.1. The conventional criteria as Advantage Depths, Advantage Ratio and Advantage Depth Dose Rate are used for evaluation of the beam quality [3].
Accelerators. Experimental nuclear reactors are not very close to the hospitals and the idea to build new small reactors for BNCT purposes is not very attractive owing to the high investment cost and to the low acceptability of such structure inside a hospital environment. Such perspective facility is accelerator based neutron source. These devices accelerate light charge particles to defined energy and let them to strike to suitable target, the neutrons are produced from nuclear reactions. The following reactions are in the center of interest:

\[ ^{7}\text{Li}(p,n)^{7}\text{Be}, \quad ^{9}\text{Be}(p,n)^{9}\text{B}, \quad ^{9}\text{Be}(d,n)^{10}\text{B}, \quad ^{13}\text{C}(d,n)^{14}\text{C}, \quad \text{fusion reaction } D-T \text{ and } D-D \text{ can be used, too.} \]

Comparing the neutron production rate and the average and maximum neutron energy it turns out that the combination of an accelerated proton beam with lithium target would provide very interesting results. As it concerns the heat removal system, the case of lithium represents probably the main issue for overcome.

The Dynamitron accelerator at the University of Birmingham has the potential to be the first clinical accelerator-based BNCT facility in the world. The accelerator has demonstrated proton currents in excess of 1 mA, lithium target generate a neutron source $1.37 \times 10^{12}$ n/s. The facility uses the Fluental™ to moderate the neutron spectrum to appropriate therapy energies. The system with a graphite reflector and Li-polyethylene shield and delimiter is shown schematically in Fig.1.
Some parameters of Birmingham facility are shown in the last column of Table 1. The Advantage Depth and Advantage Ratio are both excellent. However, it is also clear that for a 1 mA proton beam current, the Advantage Depth Dose Ratio is low, much lower than any reactor beams presented here. This fact is reflected in the long treatment time for supposed clinical trials, so far [4].

3. Calculation
The geometry of neutron source for BNCT is very complicated, see the neutron beam on LVR-15, for example.

The fast neutrons escaping the core have to be moderated to epithermal energy, the appropriate filter assembly is designed. The broad beam is collimated, reflected and shielded, the different calculation method are used for this purposes.

Two principle approaches are used for neutron (and gamma) solution of transport equation:

- deterministic methods
- statistic methods

The discrete ordinates codes ANISN, DORT and TORT are representatives of the first group, Monte Carlo code MCNP for the second one. Both methods have some advantages and some disadvantages, it depends on type of criterion (time of calculation, approximation of real geometry possibility, for example).

The calculation geometry model of channel inner parts on LVR-15 for optimization is shown in Fig. 3.
4. Measurement

Knowledge of the basic parameters of the BNCT epithermal neutron beam is one of the essential conditions ensuring the beam optimal therapeutic use. Basic calculation characterization of the beam is verified by measurement of the neutron spectrum, neutron profile, fast neutron kerma rate in tissue and photon absorbed dose. The following methods are used:

- Activation foils – for the fast, epithermal and thermal neutron fluence rates, neutron spectrum,
- Bonner spheres – for the fast, epithermal and thermal neutron fluence rates, neutron spectrum,
- Al-P glass TLD – for gamma absorbed dose,
- Twin ionization chambers – gamma and fast neutron kerma in tissue.
- Scintillation spectrometer - fast neutron spectrum, gamma ray spectrum.
- Hydrogen proportional spectrometer - fast neutron spectrum,
- Semiconductor detector with natural Li converter - thermal and/or epithermal (with Cd) neutrons,
- $^{235}$U and $^{232}$Th fission chambers - fast neutrons profile,
- $^{238}$U and $^{238}$U fission chambers – beam monitoring.

**Activation foils**
The set of the activation monitors include thermal, resonance and threshold detectors, the following reactions are often used: $^{197}$Au($n, \gamma$)$^{198}$Au, $^{115}$In($n, \gamma$)$^{116}$In, $^{45}$Sc($n, \gamma$)$^{46}$Sc, $^{238}$U($n, \gamma$)$^{239}$U, $^{186}$W($n, \gamma$)$^{187}$W, $^{139}$La($n, \gamma$)$^{140}$La, $^{55}$Mn($n, \gamma$)$^{56}$Mn, $^{63}$Cu($n, \gamma$)$^{64}$Cu, $^{115}$In($n,n'$)$^{115m}$In, $^{58}$Ni($n,p$)$^{58}$Co, $^{27}$Al($n,\alpha$)$^{24}$Na.

Neutron spectrum is evaluated using an adjustment procedure[7] which provides a means for combining reaction rates with a calculated neutron spectrum resulting in determining an optimal estimation of the thermal, epithermal and fast neutron fluence rates and their uncertainties. The SAND II [8] and BASACF [9] codes with the IRDF-90 [10] and DOSCROS84 [11] cross-section data libraries are used for the adjustment.

**Bonner spheres spectrometer**
Supplementary method used for the spectrum measurements is Bonner spheres detector consisting of a thermal neutron detector and a set of polyethylene spheres having 2", 3", 4", 5" in the diameter. The advantage of the spectrometer is that the 90% response intervals of the spheres continuously cover the epithermal part of the neutron energy range. Disadvantage of the spectrometer is their high thermal neutron efficiency resulting in the necessity to apply them at low reactor power. The spectrum...
adjustment procedure is the same as in the case of the activation foils. The neutron dosimetry data related to both the activation foils and the Bonner spheres are usually combined and unfolded together.

**Al-P glass TLD**
The standard types of TLD are used to get absolute information about the gamma absorbed dose rate in the BNCT beam and in phantom measurement. The response of the detector lies in the energy range 25 keV - 7.5 MeV and the detector can measure the gamma absorbed dose up to 10 Gy. The thermal neutron correction factor derived in a thermal neutron field [12] has to be used.

**Twin ionization chambers**
The neutron kerma rate in tissue and photon kerma rate in tissue both in the beam and in phantom can be determined with a twin ionization chambers. They are used either as air-filled or flushed with a TE-equivalent CH₄-based gas mixture (TE chamber) or with argon (Al chamber). The chambers are calibrated in the absolute ¹³⁷Cs radiation beam in the units of the exposure. Responses of the chambers to the neutrons and gamma rays respectively can be determined from measurements using different neutron and gamma sources as follows: ²⁵²Cf, ⁹Be(d,n), ⁷T(d,n).

**Scintillation spectrometer for neutrons and gamma rays**
The scintillation spectrometer is used with liquid scintillator or stilbene crystal for the detection of the fast neutrons with energies above ~ 0.5 MeV or the gamma ray spectra in the energy range of (0.4, 12) MeV. A discrimination of the signal is based on a different shape of the scintillation pulses (the PSD method).

**Hydrogen proportional spectrometer**
A hydrogen gas filled proportional counter can be used to measure fast neutron spectra lying in the energy interval (60, 1500) keV. To cover such a wide energy range, some counters filled with hydrogen of different pressures are used. The proton recoil spectrum obtained by measurement is unfolded to the neutron spectrum using a direct differentiation algorithm with a correction related to the double neutron interaction with hydrogen nuclei and to the proton escape from the detector volume.

**Semiconductor detector with Li converter**
The detector has a cylindrical shape and is made from Al and polyethylene so that it can be regarded as a tissue equivalent. Its dimensions are limited by dimensions of Si wafer which is used. The thermal neutron efficiency of the detector can be controlled by the amount of ⁶Li in the converter. Detector is used for the thermal and epithermal neutrons measurement both in the beam and in a phantom [5], [6] in the neutron fluence rate up to 10⁹ cm⁻²s⁻¹.

**Fission chambers**
Fission chambers with ²³⁵U and ²³⁸U can be used in the choice place of beam for ensure the monitoring of the beam during the patient irradiation. The monitors are calibrated relatively per epithermal neutron fluence rate in the beam. The ²³⁸U or ²³⁸Th chambers can be e also used for relative measurements of the beam profile.

**5. Results of measurements**

**Spectrum**
The spectrum calculated with MCNP was adjusted with activation foil measurement, result is presented in the Fig.4.
Fig. 4. Neutron spectrum calculated by MCNP code and adjusted to activation foil measurement. Comparison of the result for adjustment codes SAND and BASACF.

Geometry
Geometry of the beam was determined in respect to epithermal and photon rate respectively. For the first case the silicon detector encapsulated in 1 mm Cd box was used. As the radial symmetry of beam was supposed the profile was measured only in horizontal plain corresponding the beam axes. The gamma ray profile was determined by small GM tube. The relative profiles are in the Fig. 5.
6. PHANTOMS

The phantom measurements of thermal and epithermal neutron distribution and photon kerma are important especially in respect to scaling the neutron and photon source respectively. The sources are used for treatment planning calculation. The appropriate scaling ensures the realistic results in calculation of physical doses distribution in the target volume for all the components (neutron dose, boron dose, primary and induced photon dose, and proton dose). Phantoms of different forms were used in “history” of BNCT. Ellipsoidal phantom used in MIT group is seen in Fig. 6.
A cylindrical polyethylene phantom PE (diameter of 20 cm, length of 20 cm) and a phantom of the human head filled with water were used as a standard in the Czech BNCT Project. Comparison of the measured (TLD) and calculated (with MacNCTPLAN) photon kerma rate in the polyethylene phantom is shown in Fig.7, thermal neutron distribution in the human head phantom along the head "centerline" with semiconductor detector with Li radiator is seen in Fig.8.

According to international recommendation the unified phantom is used, now. It is the large water phantom of dimensions 40 cm x 40 cm x 20 cm (W x H x L) with wall of thickness 1.2 cm, entrance window 0.5 cm thick of 24 cm diameter (larger of the beam aperture).

**MONITORS**

Beam monitoring can be understood as activity in short time or long time period. In short time (during irradiation) the system of neutron and gamma detectors is applied (\(^{235}\)U and \(^{239}\)U fission chambers, GM...
tubes) to observe the reactor power fluctuation. The detectors are installed in collimator, prompt level is searched and compared with standard one. Total irradiation time is consequently corrected. Long time monitoring has to guarantee reproducible beam parameters for patient irradiation. According to requirements of state authority for quality assurance the system of tests verifying spectra, absorbed doses and geometrical characteristics of irradiation beam is applied. Real values of separate components of total dose are verified before each patient irradiation according to requirements of state authority (State Office for Nuclear Safety). The following tests are realized:

- Determination of neutron spectra at the beam aperture
- Determination of photon dose at the beam aperture
- Determination of fast neutron kerma at the beam aperture
- Control of geometry of radiation field
- Control of thermal neutron distribution in water phantom
- Normalization of source for treatment planning
- Determination of reference values for beam monitoring

All these tests are the part of complete requirements for quality assurance.

**Boron concentration measurement**

A prompt \( \gamma \)-ray analysis (PGA) facility for determination of \(^{10}\text{B}\) in biological samples was built inside the reactor hall. The 6-meter mirror neutron guide provides the neutron flux 2.8 n/cm\(^2\)/s in the target position at the reactor power of 8 MW. It is possible to reach relative efficiency 25% for detection of characteristic 478 keV \( \gamma \) line with HPGe. The device itself is shielded from a \( \gamma \)-ray and neutron background in reactor hall by a combined shielding made of Pb and Li\(_2\)CO\(_3\). The experimental set-up makes it possible to measure 1.0 or 0.5 ml liquid samples in Teflon vials at the present time. The \(^{10}\text{B}/\text{H}\) \( \gamma \)-ray signal ratio is used for determination of \(^{10}\text{B}\) concentration. The sensitivity of this facility is 4.9 counts within 478 keV Doppler broadened peak per 1 \( \mu \)g of \(^{10}\text{B}\). The facility was tested with water solutions of BSH and BPA as well as with blood solutions of BSH (see Fig.9). A good agreement was obtained between the values of \(^{10}\text{B}\) concentration by the PGA method and the values from the ICP method.

![Fig.9. The spectra for boron concentration measurement](image_url)

The configuration of PGA facility located at neutron guide of LVR-15 reactor is shown in Fig.10.
Fig. 10   The facility for boron concentration measurement in blood samples

$\text{^{10}B}$ concentration in tumor and blood is measured during surgery. All pharmacokinetics is determined. $\text{^{10}B}$ concentration in blood is measured before irradiation to put more precisely the planned dose. The $\text{^{10}B}$ concentration in blood is very personal. The results for ten patients are shown in Fig. 11.

![Graph showing boron concentration in blood for 10 patients.](image)

**Fig. 11.** $\text{^{10}B}$ concentration in blood for 10 patients

**CONSTRUCTION**

Many physical problems have to be solved during the construction BNCT facility. Shielding calculations are used for design of wall thickness of irradiation room. Inner surface is covered with borated polyethylene to absorb scattered neutrons, see Fig. 12.
Some special equipment are installed in irradiation room to ensure the full functioning. The laser is component of system for patient positioning, TV and intercom is used for communication. Appropriate manner of fixation during irradiation has to be chosen, too. Some mentioned parts are demonstrated in Fig. 13.

All technical information and the means for protection of patient are concentrated to control room, from this place the staff operates the process of irradiation. The configuration in the hall of LVR-15 is seen in Fig. 14.
Conclusion
The Czech BNCT facility has treated a group of patients according to the Phase I protocol. During the design, construction and operation of the facility the full-range experience was received in the different fields. Some results from physics presented here can be useful for next colleagues involved in BNCT projects.

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Fig. 14 Irradiation room and control room in the hall of LVR-15 reactor
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